INFLUENCE OF SOIL SPATIAL VARIABILITY AND SOIL-WATER CONDITIONS ON SELECTED HISTOSOLS IN THE EVERGLADES AGRICULTURAL AREA

By

ORLANDO ANTONIO DIAZ

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INFLUENCE OF SOIL SPATIAL VARIABILITY AND SOIL-WATER CONDITIONS ON SELECTED HISTOSOLS IN THE EVERGLADES AGRICULTURAL AREA

By

Orlando Antonio Diaz

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Chairman: Dr. Edward A. Hanlon
Cochairman: Dr. David L. Anderson
Major Department: Soil Science

Chemical properties of Histosols in the Everglades Agricultural Area (EAA) are affected by the inherent variability, management practices, and soil-water conditions. Soil spatial variability is a limiting factor affecting the reliability of predictions concerning soil properties, soil behavior, and land-use performance. Recognition of the importance of spatial variability on land use has led to the study of soil heterogeneity in greater detail. This study was conducted to evaluate the influence of field and regional soil spatial variability and soil water conditions on Histosols in the EAA. The structure of spatial dependence of selected soil chemical properties was studied by the use of semi-variograms. Block kriging was used to map field variability of four major soil series and

the regional variability of important soil chemical properties across the EAA. The effect of intermittent flooding and drained conditions on N and P release from surface soils were determined by column leaching studies.

Results showed that selected soil chemical properties in the EAA are spatially dependent. Both road and ditch spoils greatly alter soil chemical properties, although anisotropic semi-variograms showed that road spoils have a greater influence on soil variability. The range of spatial dependence of the majority of the soil properties was > 100 m at all locations.

Kriged field contour maps indicated that an area of approximately 40 to 50 m from the road and 25 to 30 m from each side of the ditch should be avoided during soil sampling. Soil variability among fields was large as judged by the number of samples required to produce repeatable test values.

Kriged regional contour maps indicated that soil variability in the EAA is largely a result of soil type and management. Estimation variance maps indicated areas where further sampling will provide additional information to improve prediction confidence levels.

In a related laboratory experiment, the amount of total N released under drained conditions was approximately 60% higher than that released under intermittent flooding conditions. However, the amount of total P released under

intermittent flooding was two to six times higher than total P released under drained conditions.

CHAPTER 1
INTRODUCTION

The Everglades Agricultural Area (EAA) contains one of the richest agricultural regions in the United States. Revenues from the EAA and adjacent areas stimulate over one billion dollars per year into the economy of South Florida. The EAA produces a large share of the sugarcane and winter vegetable consumed in this country. In addition, this region supports a sizable area of sod, rice, citrus, and cattle production.

The EAA is a relatively flat area with most soils containing 85% or more of organic matter by weight. The organic soils from this area have been extensively studied; however, there is little information regarding their nutrient distribution and spatial variability.

Soil variability is the product of soil-forming factors functioning and interacting over a continuum of spatial and temporal scales. Natural processes, such as climate, mineral and organic parent materials, flooding, and weathering, influence soil variability over long time periods. Soil variability in the EAA has been further increased by drainage, agricultural land preparation, and the extensive construction of roads and canals.

Soil variability is a major problem affecting the reliability of soil testing for fertilizer recommendations. Reliability of a soil test result largely depends on whether or not the sample used for soil testing is actually representative of the field being sampled. Whenever soil heterogeneity increases, the precision of statements concerning their properties, behavior, and land use decreases (Trangmar et al., 1985).

One tool used to measure and describe the spatial variability of soils is geostatistics. This technique has the ability to consider directly the spatial dependence of soil properties during sample interpolation. It also provides the ability to evaluate and map soil variability of selected properties. Two of the main analyses in geostatistics are semi-variogram calculations and kriging statistics. Semi-variograms are the graphic representation of the spatial variability between any two samples as distance between samples changes. Once an appropriate semi-variogram has been calculated, values at unsampled locations can be estimated through kriging.

The broad objective of this research was to obtain information of field and regional soil spatial variability of the Histosols in the EAA. The specific objectives were to (i) use semi-variograms to determine the structure of spatial dependence of selected soil chemical properties in the Histosols of the EAA; (ii) use block kriging techniques

to map and evaluate within field variability in four major soils series; (iii) summarize and map regional variation of agronomically important soil chemical properties in the EAA using geostatistical methods; and, (iv) to measure the effects of intermittent flooding and drained conditions on N and P release into drainage water of five typical Histosols from the EAA.

CHAPTER 2
LITERATURE REVIEW

The Everglades Agricultural Area

The Everglades is the largest contiguous body of organic soils in the continental United States (Hammar, 1929; Stephens, 1956). The Everglades accounts for approximately 75% of the organic soils in Florida (Davis, 1946) and about 14% of the total national deposits (Stephens, 1969). Peat and muck soils occupy approximately 778,000 ha of the Everglades (Jones, 1942). A portion of the Everglades was drained at the beginning of the century for agricultural purposes, becoming what is known today as the Everglades Agricultural Area (EAA). The EAA contains approximately 245,930 ha of organic soils (Histosols), forming one of the richest agricultural regions in the United States (McCollum et al., 1978). This area is intensively cultivated with annual cash receipts averaging more than 500 million dollars and stimulating over 1.2 billion dollars into the economy. The main crops grown in the EAA are sugarcane (*Saccharum* spp.) and winter vegetables. Sod, especially St. Augustine grass [*Stenotaphrum secundatum* (Walt.) Kuntze], rice (*Oriza sativa* L.), and cattle production accounts for the remaining

agricultural production in the EAA. Sugarcane production in South Florida occupies an area of approximately 173,344 ha yr^{-1} (Anderson, 1990a). From this total area, 89.8% (155,660 ha) is produced on the Histosols of the EAA (Coale, 1990). Winter vegetables are the second major crop grown in the EAA, utilizing an area of approximately 25,000 ha of organic soils. Rice is a relatively new crop introduced in the area during the past 10 years. In 1988, rice was grown on approximately 5850 ha in the EAA (Alvarez et al., 1989).

Geology

The Everglades is primarily a great sawgrass (*Cladium jamaicense* Crantz) marsh approximately 65 km wide and 160 km in length that extends from Lake Okeechobee to nearly the end of the Florida peninsula (Loveless, 1959; Zelazny and Carlisle, 1974). Both sides are bounded by low sandy ridges. The depth of these organic soils varies from north to south. Near the east side of Lake Okeechobee the depth of the organic materials is 2.5 to 3.5 m, but in the southern part of the Everglades they are quite shallow (Davis, 1946; Snyder et al., 1978). The depth of organic materials over a large part of the area is now less than 1 m (Soil Conservation Service, 1988; Anderson, 1990a).

The EAA is located in the upper Everglades, extending from south of Lake Okeechobee to the Broward County line (Fig. 2-1). The majority of the soils within the EAA are

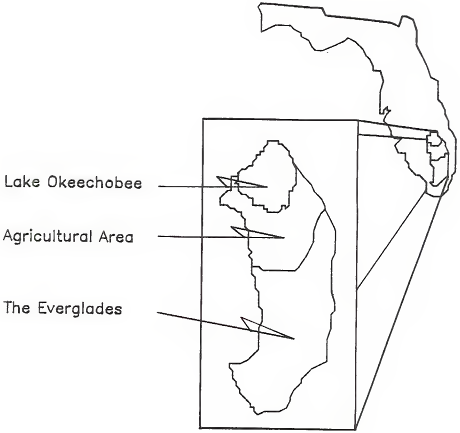

Fig. 2-1. Location of the study area and surroundings.

underlain by the Pleistocene-age Fort Thompson formation consisting of alternating beds of limestone, shell, sand, and marl, which are often perforated by solution holes. Near the southern border of the EAA, this rock formation grades into another formation of softer and more porous rock called Miami oolite. Along the western edge the organic soils are underlain by sandy material (Cooke, 1945; Snyder et al., 1978).

Formation Processes

In past geologic times, Lake Okeechobee, a circular fresh water lake approximately 1800 km^2, overflowed its south and eastern rims during the rainy season each year. This overflow, together with an annual rainfall of about 60 in (152 cm), inundated the Everglades basin and provided a suitable environment for accumulation of the present organic soils of the Everglades. The majority of these soils were derived from growth of emergent reed and sedge-like plants, principally sawgrass. These soils developed into light, brown colored, fibrous peats, which when drained, develop into excellent field soils with a black, finely-fibrous, well-decomposed organic surface.

Histosols in the EAA began to form approximately 4400 B.C. in the late Hypsithermal period (McDowell et al., 1969). Initially, approximately 500 to 4000 years were required to develop about 7.6 cm of the basal muck peat,

composed of a mixture of marl and organic matter. However, between 3500 to 1200 B.C. peat development proceeded at a rate of about 7.3 cm per century. It was during this period that the existing peat, measuring about 1.37 m in thickness, was developed. The Everglades basin before the initiation of the drainage programs in the early 1900's was inundated for a large part of the year. Water was high enough to maintain anaerobic conditions permitting continuation of peat development until shortly after 1906 when the Everglades Drainage District began construction of the first drainage canals. By 1914, the peat had developed to an average depth of 3.65 m (Stephens, 1956). This represents an average of peat development of about 8.4 cm per century. Although, the early attempts at draining the area were unsatisfactory for commercial farming, the water balance was disturbed to a point that aerobic conditions prevailed. After this time, the process of peat accumulation was reversed and destruction of the soil by microbial oxidation began (Stephens, 1956).

Soils in the EAA

The soils in the EAA are organic (Histosols), generally containing more than 85% organic matter by weight derived from hydrophytic vegetative residues. Except for Histosols found adjacent to Lake Okeechobee, their mineral content is less than 35%. In the current soil classification system,

organic soils are defined as soils containing at least 12 to 18% organic carbon (20 to 30% organic matter) by weight, depending on the clay content of the mineral fraction (Soil Survey Staff, 1975).

The major Histosol series and some of their most important characteristics are as follows.

Torry mucks (euic, hyperthermic Typic Medisaprist) are very poorly drained, deep, organic soils with a high content of fine textured mineral material. These soils have an organic layer > 130 cm over limestone. Permeability of these soils is moderate (1.5 to 5.1 cm hr^{-1}) to a depth of 91 cm and rapid (15.2 to 50.8 cm hr^{-1}) at subsequent depths. Torry soils have a high available water capacity (0.2 to 0.3 cm cm^{-1}) in all layers with a high natural fertility. A representative pedon of these soils has a black muck (sapric material) surface layer about 30 cm thick with a mineral content of about 70%. The next layer is a sticky black muck that extends to about 91 cm with about 60% of mineral material. Below 91 cm, there is a black muck that has a mineral content of about 35% and extends to a depth of about 165 cm. Torry mucks account for about 7.1% of the organic soils in the EAA.

Terra Ceia mucks (euic, hyperthermic Typic Medisaprist) are very poorly drained and deep organic soils. These soils have an organic layer > 130 cm over limestone. A representative pedon of a Terra Ceia muck has a black muck

layer of sapric material in the upper 20 cm of soil with a dark reddish brown muck underneath that to a depth of 163 cm or more. Terra Ceia mucks account for about 9.5% of the organic soils in the EAA.

Pahokee mucks (euic, hyperthermic Lithic Medisaprist) are poorly drained organic soils with organic layers from 91 to 130 cm thick over limestone. A representative pedon of a Pahokee series has a black muck layer in the upper 71 cm of soil with a dark reddish brown muck underneath that extends to the limestone bedrock at a depth of between 91 to 130 cm. Pahokee mucks account for about 27.4% of the organic soils in the EAA.

Lauderhill mucks (euic, hyperthermic Lithic Medisaprist) are poorly drained organic soils with dark organic layers from 51 to 91 cm over limestone. In a representative pedon, the surface layer is a black granular muck about 20 cm thick. Below, there is a layer of black muck about 25 cm thick that is slightly more fibrous. The next layer is dark reddish brown fibrous muck that extends to a maximum depth of 91 cm. Lauderhill mucks account for about 39.6% of the organic soils in the EAA.

Terra Ceia, Pahokee, and Lauderhill mucks are similar, differing only in the thickness of the organic material over the limestone bedrock. These soils contain less than 35% mineral matter by weight. Under natural conditions, these soils are flooded, or they have a water table within 25 cm

from the surface for 6 to 12 months. These soils have rapid permeability and very high available water capacity with a moderate natural fertility.

Dania mucks (euic, hyperthermic, shallow Lithic Medisaprist) are very poorly drained soils with an organic layer < 51 cm over sand and limestone. A representative pedon of this soil series has a black well-decomposed muck layer in the surface 10 cm of soil. The next layer is dark reddish brown muck about 30 cm thick. Below the organic material, there is a very thin layer of light gray sand resting over the limestone bedrock. Like the soils discussed above, this soil has rapid permeability when drained and a high available water capacity with moderate natural fertility. Most areas of these soils are cleared and used for improved pasture or sod production. Dania mucks account for about 10.2% of the organic soils in the EAA.

Okeechobee mucks (euic, hyperthermic Hemic Medisaprist) are poorly drained, deep organic soils formed in thick deposits of hydrophytic plant remains. A representative pedon of this soil has a black granular muck (sapric material) surface layer about 20 cm thick. Below there is a layer of black muck about 50 cm thick. The next layer is a dark reddish brown fibrous mucky peat (hemic material) about 55 cm thick. Finally, there is a dark reddish brown muck layer that extends to a depth of 165 cm or more. When

drained, permeability and available water capacity of these soils is high with moderate natural fertility. Okeechobee mucks account only for about 2.6% of the area in the EAA.

Okeelanta mucks (sandy, siliceous, euic, hyperthermic Terric Medisaprist) are very poorly drained soils, with an organic layer about 102 cm thick over sand. Permeability of these soils is very high when drained. The available water capacity is high in the organic layer and low in the underlying sandy parent material. Their natural fertility is low to moderate. In a representative pedon of this soil, the surface layer is black (sapric material) and about 20 cm thick. Below, there is a layer of dark reddish brown muck that extends to a depth of about 79 cm. Underneath the organic material there is a thick layer of very dark gray sand that changes to light gray at a depth of about 140 cm. Okeelanta mucks account for only 3.6% of the total area in the EAA (McCollum et al., 1976; McCollum et al., 1978; Soil Conservation Service, 1988; Anderson, 1990a).

Organic Soil Subsidence

Drainage of organic soils deposits for agricultural purposes results in the loss of soil through rapid breakdown of organic matter. Subsidence of the organic soils in the EAA is defined as a loss of soil depth and volume due to shrinkage, compaction, and biological oxidation (Clayton, 1943; Thomas, 1965b; Smith, 1990). Initially, the most

rapid subsidence occurs from shrinkage as the peat dries out and compaction due to the use of farm equipment. These two processes do not involve the direct loss of soil material. Biological oxidation refers to the microbial oxidation of the organic material. Products of organic matter oxidation include CO_2 and water, various form of N such as NH_4^+, NO_3^-, and soluble organic N, Ortho-P, and soluble organic P. Other factors affecting subsidence are burning, wind erosion, character of soil material, and cropping system (Thomas, 1965b; Lucas, 1982; Smith, 1990). While all the listed factors are important, the metabolic activity of microorganisms has been singled out as the largest factor affecting subsidence. The reason is because microbial activity is dynamically indefinite and largely uncontrollable. This process continues as long as the soil is drained, and eventually most of the organic material is destroyed, leaving little soil material over the underlying rock. Microbial oxidation accounts for 70% of soil subsidence in the EAA (Volk, 1973). The other factors are considered to be determinate and to some extent manageable (Volk, 1973; Snyder et al., 1978).

Subsidence has been reported to be greatest during the first few years after drainage (Clayton et al., 1952; Thomas, 1965b). During this time, shrinkage, compaction, and oxidation occur at a higher rate. Although rate of subsidence may vary with soil type and imposed crops, the

fact remains that organic soil losses due to oxidation are appreciable on any drained and cultivated organic soil. Measurements of subsidence in the EAA have shown that soil is lost at an average rate of 3 cm yr^{-1} (Stephens, 1956; Thomas, 1965b). Assuming present rates of subsidence and the fact that oxidation will occur as long as soils remain drained for cropping, Stephens (1956) predicted that by the year 2000 only about 13% of the soils in the EAA will be deeper than 91 cm, and 45% will be less than 30 cm deep. These predictions appear to be correct (Snyder et al., 1978; Soil Conservation Service, 1988). However, these soils can be conserved through better water management practices, such as using higher water tables and flooding during fallow (Snyder et al., 1978; Forbes, 1981).

Soil Variability

Some soils are not homogeneous, but rather a heterogeneous bodies of materials. Because of this heterogeneity, methods have been developed to delineate soil classification units. One type of soil variation is the variation among the several units which have been classified as homogeneous. For example, poorly drained soils formed from recent alluvium are usually different in most of their properties from well-drained soils formed from residual parent material (Petersen and Calvin, 1986). Because of the nature of soil-forming processes, distinct boundaries

between soil classification units are rare. Although two adjacent soil series may be distinctly different, there is usually a gradual transition in the field between one series and another. However, local variations within a particular soil series exist.

The nature of soil variability is scale-dependent based on soil-forming factors and processes interacting over many different spatial and temporal scales (Burrough, 1983a). Therefore, the nature of soil variability identified by spatial studies of soil properties depends largely on the scale of observation, soil properties, and methodology used to conduct the investigation (Wilding and Drees, 1983). Variation in soil properties from one point in the landscape may result from natural causes such as vegetation, topographic changes, or from man-made variations such as fertilizer application (Beckett and Webster, 1971).

Wilding and Dress (1978) pointed out that spatial soil variability can be grouped in to two broad categories, systematic and random. Systematic variability is expressed as gradual or distinct changes in soil properties that can be explained by the soil-forming factors or processes at a given scale of observation. Sources of systematic variation may range from differences in topography, lithology, climate, biological activity, and age of soils in regional studies (Van Wambeke and Dudal, 1978) to differences in microfabric and physicochemical composition when soils are

studied on a micro level (Miller et al., 1971). Associated with systematic variation are differences in observed soil properties that cannot be related to a known cause. There are also spatial, temporal, and measurement sources of variation which cannot be explained by the scale of investigation (Ball and Williams, 1968). This unexplained heterogeneity is termed random, noise, or chance variation (Burrough, 1983b; Wilding and Drees, 1983).

Soil variability is the product of soil-forming factors operating and interacting over a continuum of spatial and temporal scales. Processes that operate over large distances such as climate produce gradual soil changes, although abrupt changes may occur between two climatically determined plant communities (Beckett and Webster, 1971). Other processes, such as parent material and soil weathering influence soil variability over long time periods. According to Robinson and Lloyd (1915), soils formed on transported materials tend to be more variable than those weathered from bedrock <u>in situ</u>. Even within an outcrop of an apparently uniform sedimentary rock, there can be regional soil differences, as a result of geochemical gradients at the time of deposition (Ulrich, 1949). Regional contrasts in topography can produce regional differences in soil properties. Within a region, dissection and the associated deposition of eroded materials can produce recurrent patterns of land forms, and as a result,

recurrent patterns of dissimilar soils (Beckett and Webster, 1971).

Within the soil profile some physical and chemical properties tend to increase lateral variability, such as the development of 'gilgai' or of frost-wedges (Crompton, 1956). Many biological activities increases local variability also. Ebersohn and Lucas (1965) reported that the localized uptake of nutrients and water or their concentration beneath the tree canopy increase localized soil variability beneath the canopy. Similarly, tree-throw, burrowing or wallowing animals, termite and ant mounds, produce soil heterogeneity (Lyford and MacLean, 1966).

The effects of all these factors are superimposed, affecting the overall soil variability. Processes that give rise to soil differences over short distances introduce variability within all sampling areas regardless of their size. Long-range soil changes caused by soil processes will on the average make noticeable contributions only to the variability of larger sampling areas. Therefore, the overall variability of the soil within an area depends strongly on the environment, but soil variability is likely to increase with the size of the area sampled (Beckett and Webster, 1971).

Variability of soil chemical properties can be increased on cultivated soils. Intense grazing produces dung or urine patches rich in P and K, respectively (Friesen

and Blair, 1984). Uneven fertilizer or manure application, row cultivation, and the growth of row or tree crops, all tend to superimpose additional heterogeneity on soil chemical properties. Melsted and Peck (1973) reported that where fertilizers have been applied, large differences in nutrient levels can be found in different parts of the same field. These differences are not necessarily sampling errors, but a reflection of the true soil variation within the field.

Soil properties vary on both the horizontal and vertical planes. Horizon boundaries may be more distinct than surface boundaries within a soil classification unit. This should be taken into consideration when sampling soils. As the soil heterogeneity increases, the precision of statements concerning their properties, behavior, and land use performance decreases (Trangmar et al., 1985). Therefore, researchers have suggested the subdivision of soil populations, both horizontally and vertically, into sampling strata which are as homogeneous as possible. In addition, all possible sources of variation within the population should be sampled if valid inferences are to be made about the population from the sample (Petersen and Calvin, 1986).

Geostatistics

Most soil properties are spatially correlated, but cannot always be spatially measured or recorded. Therefore, in order to interpolate the values of individual variables or class types at unsampled locations, variability information recorded at sampled sites is used (Burgess and Webster, 1980a; Oliver, 1987). In soil science, spatial variation has been defined largely by the spatial classification of either individual properties or of class types. The classical approach in the field is to group soils together in similar units or lay out small plots with the assumption that variability within the plots is purely random. These assumptions have held more or less at the broad scale. However, as attention has increasingly focused at the local scale, and the need has arisen for quantitative estimates of individual variables, spatial classification has not worked efficiently (Webster, 1985; Oliver, 1987).

When spatial dependence of soil properties exits in most sampling units, the classical statistical model is inadequate for interpolation of spatially dependent variables. Classical statistical model assumes random variation and takes no account of spatial correlation and relative location of the sample (Trangmar et al., 1985; Oliver, 1987). Recent development in statistical theory has enabled spatial dependence of soil properties to be directly considered for sample interpolation. These developments are

based on the theory of regionalized variables (Matheron, 1963). A variable is considered to be a regionalized variable if it varies from one place to another with continuity. Often the regionalized variable cannot be represented by traditional statistical functions (Davis, 1973). Regionalized variable theory was developed from empirical ideas of D.G. Krige in the gold mines of South Africa. He suggested that the spatial estimation of gold content could be improved by taking the degree of similarity, or autocorrelation, between samples into consideration. The regionalized variable theory takes into account both the random and structured characteristics of spatially distributed variables to provide quantitative tools for their description and optimal unbiased estimation. This theory now forms the basis of procedures for analysis and estimation of spatially dependent variables. These procedures are known collectively as geostatistics (Journel and Huijbregts, 1978).

Geostatistics was primarily developed for the mining industry (Matheron, 1963). Geostatistics was very useful for engineers and geologists for studying the spatial distribution of important properties such as grade, thickness, or accumulation of mineral deposits. However, it has been emphasized that the estimation technique can be used wherever a continuous measure is made on a sample at a particular location in space or time. Especially where

sample estimates are expected to be affected by their position and their relationships with their neighbors (Clark, 1979a). Geostatistics is also helpful in quantifying spatial and inter-variable correlations, designs of optimum interpolation schemes, and consideration of scale of sampling. In addition, new sampling locations can be defined to improve estimates for a total population or location (Warrick et al., 1986).

Semi-variograms

Normally, samples taken in close proximity will be more related than samples taken farther apart. In geostatistical terms, if the samples are highly related, then the variance of the distribution of their differences will be low, and vice versa (Davis, 1973, Clark, 1979b). Consequently, this variance is a measure of the influence of samples over neighboring areas. The variance between samples as it relates to distance from each other is represented by a variogram, a graph of sample variance vs. the distance h. Huijbregts (1975) mathematically described a variogram, $2\Gamma(h)$, as the average quadratic deviation between values, (Y), at two points, x and x+h, or space

$$2\Gamma(h) = E([Y(x+h) - Y(x)]^2) \qquad (1)$$

However, the half-variogram or semi-variogram, $\Gamma(h)$, is more commonly used (Clark, 1979b).

The application of the regionalized variable theory assumes that the semi-variance between any two samples in the study region depends only on the distance and direction of separation between each other and not on their geographic location. Based on this assumption, the average semi-variogram for each lag distance h, can be estimated for a given value of three-dimensional space (Trangmar et al., 1985).

The equation used in calculating a semi-variogram is

$$\Gamma(h) = 1/2N(h)\ \Sigma\ [Y(x+h) - Y(x)]^2 \tag{2}$$

where $\Gamma(h)$ is the semi-variogram,

$N(h)$ is the number of pairs of points used in the calculation,

Y represents the measured values in space separated by a distance along the distance h.

The semi-variogram is defined as one-half of the variance of the differences between points separated by a distance h. The semi-variogram represents the average rate of change of a property with distance. The shape of the semi-variogram describes the pattern of spatial variation in terms of its magnitude, scale, and general form. The shape of the experimental semi-variogram may take many forms, depending on the data and sampling interval used. Ideally, the experimental semi-variogram should pass through the origin when the distance of sample separation is zero.

However, many soil properties have nonzero semi-variances as the distance (h) approaches zero.

A nonzero semi-variance is called the "nugget variance" or "nugget effect" (Journel and Huijbregts, 1978). The nugget variance (Co) represents unexplained or random variance caused by measurement error. It may also be that the sampling scheme was too far apart to eliminate all positional variability. Ideally, when the distance becomes very large, samples are independent of one another. The semi-variogram value will then become more or less constant since it represents the difference between sets of independent samples. The distance at which samples become independent of another is called the "range" of spatial dependence (A). The semi-variance value at which the graph becomes constant is called the sill (C+Co) of the semi-variogram (Fig. 2-2).

When a well-defined model cannot be fit to the calculated semi-variance values, a pure nugget effect exists in the data. A pure nugget effect means that all the calculated $\Gamma(h)$ values are equal to the sill at all values of h. The pure nugget effect is indicative of a completely random distribution of the variable at the sampling interval used. Decreasing the sampling distance will often reveal structure in the apparently random effects of the pure nugget variances (Burrough, 1983a).

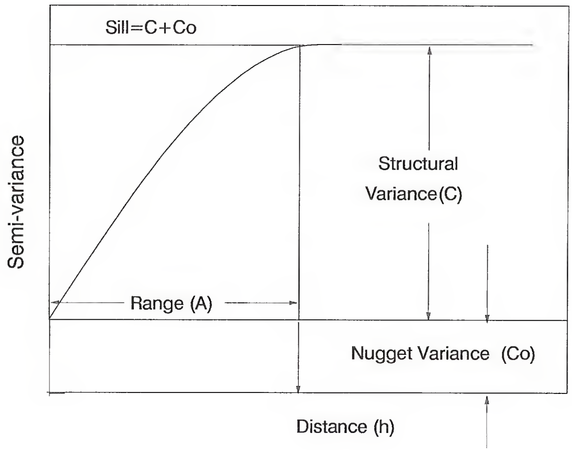

Fig. 2-2. Typical semi-variogram.

The semi-variogram is central to geostatistics and the single most important tool in geostatistical applications to soils. Mathematical functions for semi-variograms must be positive-definite functions to insure that estimation variances will be nonnegative (McBratney and Webster, 1986; Marx and Thompson, 1987; Oliver, 1987). Only models with functions that are positive-definite in up to three dimensions are considered in this chapter. The most commonly used models for the semi-variograms are given below.

A. Unbounded.

1. Linear model.

$$\Gamma(h) = C_0 + wh \qquad \text{for } h > 0 \qquad (3)$$

$$\Gamma(0) = 0 \qquad (4)$$

where Γ = semi-variance

C_0 = intercept or nugget variance

w = slope

h = lag distance

B. Transitive - models that reach a sill.

1. Spherical model - reaches a sill at a definite range.

$$\Gamma(h) = C_0 + w\,[1.5\,(h/a) - 0.5\,(h/a)^3] \qquad (5)$$

$$\text{for } 0 < h \leq a$$

$$\Gamma(h) = C_0 + w \qquad \text{for } h > a \qquad (6)$$

$$\Gamma(h) = 0 \qquad (7)$$

where a = range

$C_0 + w$ = sill

2. Exponential model - reaches a sill asymptotically.

$$\Gamma(h) = C_0 + w\,[1 - \exp(-h/a)] \quad \text{for } h > 0 \tag{8}$$

$$\Gamma(h) = 0 \tag{9}$$

In the unbounded models, the variance appears to increase without limit. The linear model is the most common in this group. The other major group is the transitive models which use a finite variance derived from moving-average processes. The spherical and exponential models are the most commonly used transitive models (McBratney and Webster, 1986).

Examples of these semi-variograms are shown in Fig. 2-3. The semi-variogram can be estimated in different directions to detect anisotropy in the variation. It can also be estimated from irregularly scattered two-dimensional data by grouping lag intervals by distance and direction (Webster, 1985).

Semi-variograms can be used to optimize sampling (Campbell, 1978; Burgess et al., 1981; McBratney et al., 1981). Campbell (1978) used semi-variograms to study spatial variation of sand and pH measurements within each of two sampling areas displaying contrasting pattern of variation. He was one of the first to use geostatistical methods in soil science. McBratney et al. (1981) explained that an optimal sampling scheme is based on the theory of

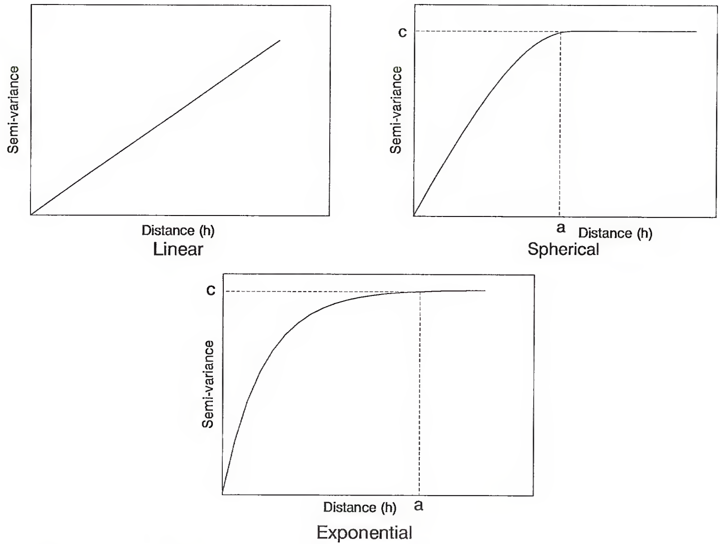

Fig. 2-3. Most commonly used theoretical semi-variograms.

regionalized variables that assumes that spatial dependence can be expressed quantitatively in the form of the semi-variogram. Assmus et al. (1985) used semi-variograms to describe the field spatial variability of P. These authors concluded that if a strong relationship exists, the minimum sampling distance should be equal to the range of the semi-variogram model.

Semi-variograms are also used to study spatial variability of soil properties over small distances (Vieira et al., 1981), and over large distances (Yost et al., 1982a; Uehara et al., 1985; Xu and Webster, 1984). Vieira et el. (1981) used a sampling distance from 1 to 19 m to measure the spatial variability of infiltration rates in Entisols. Semi-variograms indicated that samples separated by 50 m or more were unrelated. Yost et al. (1982a) collected soil samples along transects on the Island of Hawaii at 1 and 2 km intervals to determine spatial dependence of soil chemical properties over long distances. They concluded that soil chemical properties were spatially dependent.

Kriging Statistics

The estimation procedure incorporated into the regionalized variable theory is known in soil science as kriging, after D.G. Krige. Krige was the scientist that empirically devised the kriging technique for use in the South African goldfields (Webster, 1985). Kriging is a

method used to spatially predict soil properties. It is an optimal geostatistical procedure in the sense that it provides estimates of values at unrecorded places without bias and with minimum and known variance. Kriging is essentially a means of local estimation in which each estimate is a weighted average of n observed values (Burgess and Webster, 1980a; Webster and Burgess, 1983). The kriging technique outside the mining industry is relatively new; however its popularity in other disciplines has increased in the last 15 years. Kriging has been used successfully in mining (David, 1977), hydrology (Delhomme, 1978), and soil science (Vieira et al., 1981; Yost et al., 1982b). The simplest forms of kriging are point and block kriging. Both techniques assume that the sample data are normally distributed and stationary (Henley, 1981).

Point estimation is considered to be the most common kriging technique used in soil science (Burgess and Webster, 1980a; Vieira et al., 1981). The interpolation of the regionalized variable Z at a location x_0 is

$$\hat{Z}(x_0) = \sum_{i=1}^{n} f_i \, Z(x_i) \tag{10}$$

where $\hat{Z}(x_0)$ = unknown parameter at location x_0,
f_i = weights associated with data points,
$Z(x_i)$ = value of a property at a point x_i.

The weights are dependent on the semi-variogram, and the configuration of sampling points, with more weight being

given to nearby points (Oliver, 1987). The weights are chosen so that the estimate $\hat{Z}(X_0)$ of the true value $Z(X_0)$ is unbiased and the estimation variance is minimized (Trangmar et al., 1985).

Most of the early applications of kriging in soil science involved simple point estimation for isoproperty mapping (Burgess and Webster, 1980a; Vieira et al., 1981; Webster and McBratney, 1987). Webster and McBratney (1987) used point kriging to map extractable P, exchangeable K, and pH in the surface soils from the Broom's Barn Experimental Station. An area of 77 ha was used in this study, with samples taken at 40-m intervals. Semi-variograms of the properties were determined and kriged values estimated at 10-m intervals using a square sampling grid. These values were contoured to produce maps of the properties. Point kriging has been found to be one of the most practical methods for mapping soil pH with high precision (Laslett, et al., 1986; Webster and McBratney, 1987). The most attractive feature of kriging for mapping is that besides the unbiased estimation of values, it provides an indication of the reliability of the estimates.

Point kriging is also used in the estimation of variances for designing sampling schemes for future kriging operations (Burgess et al., 1981; Marx and Thompson, 1987). In addition, point kriging has the ability to define the direction and magnitude of soil variability using a minimum

of subsamples. This technique may have its greatest advantage in the determination of plot size and shape in selection of field research areas (Sabbe and Marx, 1987).

When an estimation is made from averages, the procedure is called block kriging (Burgess and Webster, 1980b). Block kriging has the capability to interpolate an average value for an area or block larger than the soil area actually sampled. This procedure can avoid some of the weakness of point kriging, resulting in smaller estimation variances and smoother maps (Burgess and Webster, 1980b; Trangmar et al., 1985). The estimation variance of block kriging is always less than that of the point kriging because the within-block variance is removed from the error term. Burgess and Webster (1980b) reported up to 20-fold improvements in average estimation precision using block kriging compared to point kriging.

The most common use of block kriging has been for the production of isarithm maps of soil properties (Burgess and Webster, 1980b). They found that soil properties mapped in two intensive surveys had large nugget variances leading to large estimation variances and erratic isarithms when mapped by point kriging. They concluded that if the interest is estimation of average values for soil properties over areas rather than the estimation of specific points, then block kriging is more appropriate than point kriging. Previous studies have shown that block kriging produces smoother maps

than punctual kriging by interpolating average values for blocks, with the effect of smoothing local discontinuities (Trangmar et al., 1985). Block kriging has also been applied to interpolate spatial effects of crop response to variability imposed by soil management practices. Tabor et al. (1984) used block kriging to determine the spatial variability of nitrates in cotton petioles. They found that calculated variograms and block-kriged maps of petiole nitrates indicated a strong influence due to cultural practices, such as direction of rows and irrigation.

Intensive sampling is required to obtain good kriged estimates and for some properties this can be to costly. However, if the property of interest is spatially correlated with another property that can be measured easier, then it can be estimated more precisely from fewer observations of the other property. The procedure used in this kind of estimation is called co-kriging (McBratney and Webster, 1983b; Vieira et al., 1983). To apply co-kriging, it is necessary to model variograms for each variable separately as well as cross-variograms for all pairs. The theoretical basis as well as examples showing how to use this technique have been extensively documented (Myers, 1982; McBratney and Webster, 1983a, 1983b; Vauclin et al., 1983).

Some of the assumptions required for kriging is that the data are stationary or specifically follow the intrinsic hypothesis (Webster and Burgess, 1980; Trangmar et al.,

1985). The intrinsic hypothesis states that the variability between any two samples depend on the distance between them, but not on their spatial position. Therefore, two samples separated by the same distance, should have the same variability (Trangmar et al., 1985). Universal kriging was designed to overcome the effect of non-stationarity and permit the use of kriging in the presence of strong trends (Webster and Burgess, 1980). Universal kriging is a form of interpolation that uses local data trends to minimize the estimate error. The presence of such trends are identified qualitatively, and their form is quantitatively found by structural analysis, which simultaneously estimates semi-variances of the differences between the drift and the actual data. The resulting semi-variograms are used for the interpolation.

Webster and Burgess (1980) were some of the first researchers to apply universal kriging in soil science. They applied this method to measurements of electrical resistivity in the soil from samples collected at 1-m intervals. They concluded that universal kriging was not always applicable for soil survey mainly because of the large variances usually encountered. Yost et al. (1982b), working with large areas in the Island of Hawaii pointed out that universal kriging resulted in little improvement over ordinary kriging when comparing the observed and estimated points. Their results showed that ordinary kriging is

useful in summarizing and interpreting soil analyses and that it seems quite robust to certain degrees of nonstationarity. However, other scientists have found the technique useful in evaluating soil variability of selected soil properties. Ovalles and Collins (1988) used universal kriging to study the spatial variation of selected soil properties in northwest Florida. They found that their kriged maps of selected soil properties were helpful in locating areas of large standard errors in NW Florida. These results indicated the need for more intensive sampling at specific locations. The authors suggested that kriged standard error maps can be used to plan future sampling strategies.

CHAPTER 3
SOIL SPATIAL VARIABILITY OF SELECTED CHEMICAL PROPERTIES IN THE EVERGLADES AGRICULTURAL AREA. I. SEMI-VARIOGRAMS

Introduction

The inherent variability of soil properties is widely recognized (Beckett and Webster, 1971). Recognition of the importance of spatial variability on land use has led to the study of soil heterogeneity, at different levels of generalization. Some studies have looked at spatial variability ranging from zonal or regional differences, such as between soil orders, suborders, or great groups (Van Wambeke and Dudal, 1978; Trangmar et al., 1984), to small changes in physical and chemical properties of surface soils occurring within areas of 4 m^2 (Moormann and Kang, 1978).

Soil spatial variability is a major problem affecting the reliability of soil testing for fertilizer advisory purposes. A continuous concern within the soil-testing system is whether or not a soil sample represents the field being sampled. Cameron et al. (1971) pointed out that the three major sources of soil variation in soil testing are: laboratory, temporal or seasonal, and spatial or field. They found that spatial or field variation was responsible for the largest and most significant variation in soil

testing. As the heterogeneity of soil increases, the precision of statements about their properties, behavior, and land-use performance decreases. Predictions at unsampled locations can be estimated from information obtained at the known locations. The precision of such extrapolation is strongly influenced by the variability of soils both within sampling units and between locations (Trangmar et al., 1985).

One tool being used to measure and describe soil spatial variability is the semi-variogram. The semi-variogram represents the variability between samples across distance and its shape describes the spatial variability in terms of its magnitude, scale, and general form. Semi-variograms have been used extensively in the mining field. The interest in the application of this technique to the field of soil science has increased in the last 15 years.

Analysis of spatial dependence using semi-variograms has contributed to our understanding of many aspects of soil variability, genesis, management, and interpretation (Vieira et al., 1981; Yost et al., 1982a; Ruso, 1984; McBratney and Webster, 1986; Bos et al., 1984). Campbell (1978) computed semi-variograms to describe the spatial variability of soil texture and pH of loess and glacial-till-derived soils. Assmus et al. (1985) used semi-variograms to describe field spatial variability of P levels. They concluded that if there is a strong spatial relationship, the minimum sampling

distance should be equal to the range determined by the semi-variogram model. Burgess and Webster (1980a), created semi-variograms to show variability of sodium content, stoniness, and loam thickness from detailed soil surveys of Central Wales and Norfolk, England. Bos et al. (1984) used semi-variograms to study the spatial variation of selected chemical properties of surface soil in reclaimed phosphate-mine lands. They found that a spatial correlation generally existed at sampling distances ranging from less than 2.6 to 7.1 m.

Semi-variograms have been applied to measure spatial dependence of soil properties at small (Gajem et al., 1981) as well as large distances (Yost et al., 1982a; Xu and Webster, 1984). Gajem et al. (1981) used semi-variograms to determine the spatial dependence of selected physical properties of a Typic Torrifluvent sampled at 0.02-, 0.2-, and 2-m intervals. They reported a range of 0.6 m of spatial dependence of soil properties sampled at 0.2-m intervals. Yost et al. (1982a) determined semi-variograms of several chemical properties over the Island of Hawaii. They found a spatial dependence range of 58 km for P sorbed at 0.2 mg P L^{-1} from samples taken at 1- to 2-km intervals.

The primary objective of this study was to determine the structure of spatial dependence of selected soil chemical properties in the organic soils of the EAA. The secondary objective was to examine and interpret the use of

semi-variograms as a tool to detect withing-field soil variability.

Materials and Methods

Collection and Preparation of Soil Samples

Surface samples (0 to 15-cm depth) of four different soil series found in the EAA were used in this study (Table 3-1). Samples from two adjacent fields (A and B) were collected from each soil series during the summer of 1987. Surface samples of Lauderhill muck (euic, hyperthermic Lithic Medisaprist) were collected from both a sod, St. Augustine grass [*Stenotaphrum secundatum* (Walt.) Kuntze], and a fallow field. The fallow field (A) had been in sugarcane production (*Saccharum* spp.) for the past 5 years. Pahokee muck (euic, hyperthermic Lithic Medisaprist) samples were collected from two fields that had been in continuous sugarcane production for the past 5 years. Okeelanta muck (euic, hyperthermic Terric Medisaprist) samples were collected from two adjacent fields that had a history of sugarcane production for the previous 5 years. However, at the time of sampling, field A was previously in sweetcorn (*Zea mays* L.) production (harvested one week before sampling), and field B was in fallow. Torry muck (euic, hyperthermic Typic Medisaprist) samples were collected from sugarcane and fallow fields near the city of Pahokee. Field

Table 3-1. Description of four organic soils from the EAA used in the spatial variability study.

Soil series	Classification	Crop history	Location Rng	Twn	Sec
Lauderhill	euic, hyperthermic Lithic Medisaprist	A-Fallow B-Sod	37	45	19
Pahokee	euic, hyperthermic Lithic Medisaprist	A-Sugarcane B-Sugarcane	38	45	6
Okeelanta	euic, hyperthermic Terric Medisaprist	A-Sweetcorn B-Fallow	39	43	2
Torry	euic, hyperthermic Typic Medisaprist	A-Sugarcane B-Fallow	37	42	29

Table 3-2. Sampling distances used in the study.

Soil series	Sampling scheme	Size of study area	Sampling distance
		--- ha ---	--- m ---
Lauderhill	Large	14.2	44.8
	Small	0.8	10.0
Pahokee	Large	14.0	44.2
	Small	0.8	9.8
Okeelanta	Large	13.3	43.3
	Small	0.8	9.6
Torry	Large	13.2	43.3
	Small	0.8	9.8

A has been in continuous sugarcane production for the last 5 yr, while field B was fallow with a history of sweetcorn production.

Two different sampling schemes (Fig 3-1) were used for each location. Samples were taken on triangular grid intercepts with the purpose of increasing the number of equidistant neighboring points. The first sampling scheme included an area ranging from 13.2 to 14.2 ha covering two adjacent fields. This sampling was designed to detect differences due to ditches between fields. Lag distances used in this sampling varied from 43 to 45 m according to the size of each individual field (Table 3-2). The side of each field parallel to the access road was used as a base line for a triangular grid of 10 rows and 10 columns with a total of 100 samples taken from each location.

The second sampling scheme was designed to account for soil spatial variability that could not be measured at the larger distances used in the first sampling scheme. For the second sampling scheme, four small areas of approximately 0.2 ha were randomly located within the larger sampling grid at each location (Fig. 3-1). The lag distance used on this sampling varied from 9 to 10 m depending on the location (Table. 3-2). Extra samples (*) were taken along the ditches to guarantee detection of soil variability due to ditch spoils.

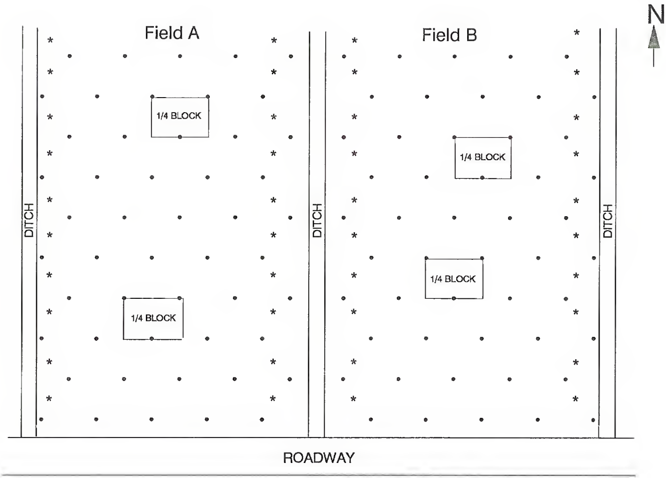

Fig. 3-1. Field sampling pattern used in the spatial variability study.

Soil samples were composites of 10 cores taken around each sampling point (0.5 m^2). Soils were air-dried at 38 °C for 72 h and passed through a 2-mm sieve before chemical analysis.

Laboratory Analysis

Soil pH was determined in a 1:2 soil:water suspension (pH_w), and 1:2 soil:0.01 M $CaCl_2$ suspension (pH_s) by glass electrode. Extractable nutrients were measured using Mehlich-I extracting solution (Ca_{MI}, Mg_{MI}, K_{MI}, P_{MI}, Zn_{MI}, Cu_{MI}, Mn_{MI}, and Fe_{MI}) (Mehlich, 1953) by the IFAS Analytical Research Laboratory, University of Florida, Gainesville (Hanlon and DeVore, 1989). Soil samples were analyzed also by the Everglades Soil Testing Laboratory, Belle Glade, for water and 0.5 M acetic acid-extractable P (P_w and P_a, respectively; 4:50, soil:solution by volume) and 0.5 M acetic acid-extractable K, Ca, and Mg (K_a, Ca_a, and Mg_a, respectively; 10:25, soil:solution by volume) (Thomas, 1965a; Sanchez, 1990).

Ash content was determined by igniting 5 g of oven-dried soil at 500 °C for 5 h. Weight loss was considered as the amount of organic matter in the sample and the residue was taken as the mineral content. The residue was dissolved in 2 M HCl and total elements with the exception of P from the Torry muck, were analyzed using the inductively coupled argon plasma (ICAP) technique. Total P content in the Torry

muck was measured by igniting 1 g of oven-dry soil at 550 °C for 2 h (Olsen and Sommers, 1982). Ash was dissolved in 6 M HCl and analyzed colorimetrically (Murphy and Riley, 1962). All laboratory results are reported on a weight basis.

Statistical Analysis

Mean, range, variance, and coefficient of variation were computed using Statistical Analysis System software (SAS, 1982a, 1982b). The Univariate procedure was used to test for normality. Approximation of each variable to normal and log (base e) normal probability distributions were determined using the Kolmogorov-Smirnoff D statistic. Variables that failed to meet the normality test were log transformed before analysis.

Semi-variograms

Geostatistical approaches applied in this study were derived from concepts discussed by David (1977) and Journel and Huijbregts (1978). Data from each location were entered in a X, Y, and Z (soil property) format. The program used in the calculation and fitting of semi-variograms was VAR5, Version 2.0. This program was part of a set of geostatistical analysis programs developed by the Department of Agronomy and Soil Science, University of Hawaii (Yost et al., 1989). Semi-variograms were calculated from the formula

$$\Gamma(h) = 1/2N(h)\ \Sigma[Y(x) - Y(x+h)]^2$$

where N is the number of sample pairs at each distance interval (h), and Y(x) is the value of the soil property at field location (x). The semi-variogram is the plot of $\Gamma(h)$ as the ordinate, against the average lag distance (h), as the abscissa (Fig. 2-2). Semi-variances were averaged over 180 degrees (considering all samples) and averaged over 90 degrees in four directions (N-S, NE-SW, E-W, and NW-SE) to determine if roads and ditches had influence in the direction of the semi-variance (anisotropy).

A reliable semi-variogram is obtained when intervals are chosen such that the number of pairs is large enough to ensure accurate definition of each point on the semi-variogram. Intervals distances (h) that were selected provided at least 25 pairs of points for each interval. This number of paired points has been found to be necessary to provide stable estimates for the semi-variogram. Another important practical consideration is that experimental semi-variograms should be considered only for small distances ($h < L/2$), where h is the lag distance and L is the dimension of the field on which the semi-variogram has been computed (Journel and Huijbregts, 1978). Weighted least squares methods using the SAS nonlinear method were used to model linear and spherical semi-variograms.

Results and Discussion

Soil Series Variation

The mean, range, variance, and % CV of selected soil chemical properties from the surface 15 cm of each soil series are presented in Appendix A. Means of selected soil chemical properties are shown in Table 3-3. Samples close to the road were not included in calculations. Soil pH_w varied from 4.8 to 6.3, with Lauderhill muck showing the highest pH_w and the Okeelanta muck the lowest pH_w. The higher pH_w of Lauderhill muck may be due to the greater effect of the limestone bedrock as the organic layer gets shallower due to subsidence. Flooding, high water tables, and calcareous deposits along roads and canal are additional factors that tend to increase soil pH over time in the organic soils of the EAA (Lucas, 1982). The acidity of organic soils is due to the presence of organic compounds, exchangeable hydrogen and aluminum, iron sulfide, and other sulfur minerals. Okeelanta muck showed the lowest pH_w and the Fe_{MI} concentration. Under natural conditions most of these organic soils are unfertile and acidic, requiring lime and fertilizer application for commercial crop production.

The presence of soluble salts influences soil pH, and to obtain a true estimate of the acidity of the soil these salts must be removed before a pH determination. Schofield and Taylor (1955) suggested the use of 0.01 $\underline{M}$ $CaCl_2$ for soil

Table 3-3. Means of soil chemical properties from the surface 15 cm of four organic soils from the EAA.

	Soil series			
Variable	Lauderhill	Pahokee	Okeelanta	Torry
	- Analytical Research Laboratory, Gainesville† -			
pH-H_2O	6.3	5.3	4.8	5.4
pH-$CaCl_2$	6.0	5.1	4.4	5.0
Ca, g kg^{-1}	9.4	10	8.6	6.8
Mg, g kg^{-1}	1.5	1.3	0.58	0.72
K, g kg^{-1}	0.36	0.22	0.37	0.46
P, mg kg^{-1}	46	49	32	94
Zn§, mg kg^{-1}	1.2	1.8	11	10
Cu, mg kg^{-1}	0.33	0.41	0.55	0.28
Mn, mg kg^{-1}	0.95	7.3	10	28
Fe, mg kg^{-1}	4.2	2.9	20	7.4
	-------- Soil Testing Laboratory, EREC‡ --------			
P_w, mg kg^{-1}	12	41	37	25
P_a, mg kg^{-1}	77	65	49	78
K, g kg^{-1}	0.29	0.35	0.29	0.29
Ca, g kg^{-1}	-	6.4	4.0	3.0
Mg, g kg^{-1}	-	1.1	0.35	0.48
No. samples	184	186	181	185

† Mehlich I-extractable nutrients.
‡ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).
§ Mehlich I-extractable Zn and Cu from Lauderhill muck were calculated from 84 observations.

pH_s measurements. This method estimates the activity of H-ions in a soil suspension in the presence of the salt added (0.01 M $CaCl_2$) to approximate a constant ionic strength of the soil regardless of past management, mineralogical composition, and natural fertility level (McLean, 1982). Measurement of soil pH_s with 0.01 M $CaCl_2$ decreased soil reaction in all samples 0.3 to 0.4 pH units (Table 3-3).

The Mehlich-I procedure extracted higher amounts of Ca, Mg, and K, than the 0.5 M acetic acid from the EREC Soil Testing Laboratory (Table 3-3). Soil K_{MI} concentrations varied from 0.22 to 0.46 g kg^{-1}, while K_a varied from 0.29 to 0.35 g kg^{-1}. Soil P_{MI} concentrations varied from 32 to 94 mg kg^{-1} and P_a varied from 49 to 78 mg P kg^{-1} with Torry muck showing the highest and Okeelanta the lowest concentration. Torry muck is one of the most productive soils in the EAA. Total P content in these soils (2310 mg P kg^{-1} of soil) is three to four times higher than total P content in Lauderhill and Pahokee mucks, and more than six times higher than total P content in the Okeelanta muck (Appendix A). Water extractable-P ranged from 12 to 41 mg kg^{-1} with Pahokee showing the highest and Lauderhill the lowest concentrations. The low P_w values shown by the Lauderhill muck is probably due to the closeness of the limestone bedrock to the soil surface increasing sorption and precipitation of P by exchangeable Ca or $CaCO_3$.

Most of the micronutrients (B, Cu, Fe, Mn, Mo, and Zn) have been found to be deficient in organic soils for plant growth and their availability is greatly affected by soil pH (Lucas, 1982). Soil Zn_{MI} concentrations ranged from 1.2 to 11 mg kg^{-1} with Lauderhill muck yielding the lowest concentration. Lauderhill muck also had the highest pH_w. Zinc deficiency has been identified in several crops grown on organic soils, which is more evident when the pH_w is above 6.5 or when acid organic soils are limed (Lucas, 1982). Soil Cu_{MI} concentrations ranged from 0.28 to 0.55 mg kg^{-1}. Copper is usually deficient when virgin Histosols are brought into production (Allison et al., 1927). Mehlich I-extractable Mn and Fe varied from 0.95 to 28 and 2.9 to 20 mg kg^{-1}, respectively, with Lauderhill muck showing the lowest concentration, as expected. Manganese is greatly dependent on soil reaction. Serious Mn deficiencies in many crops occur at pH ranges of 6.3 to 7.5. Anderson and Ulloa (1989) reported Mn deficiency in sugarcane fields above pH 7.5.

Semi-variogram Analysis

Sample probability distributions of the majority of the parameters were lognormal as determined by the Kolmogorov-Smirnoff D statistics. Therefore, most of the geostatistical analyses were performed on log-transformed data. Isotropic (direction-independent) and anisotropic

(direction-dependent) semi-variograms were calculated for each parameter at each location. Key parameters for direction-dependent and direction-independent semi-variograms for the four soil series studied are given in Tables 3-4 through 3-6, and Tables 3-7 through 3-10, respectively. The intercept (nugget variance) is the estimate of Γ at $h = 0$ and provides an indication of short-distance variation. The range is the distance (h) at which Γ reaches the maximum value (sill). The sill often approximates the sample variance (Journel and Huijbregts, 1978). The range (distance, m) is interpreted as the diameter of the zone of influence and represents the average maximum distance over which a soil property of two samples is related (Yost et al., 1982a). The range provides an estimate of areas of similarities.

Ideally the semi-variogram should pass through the origin when the distance $h = 0$. However, many soil properties, such as pH_w, Mn_{MI} and Cu_{MI} have nonzero semi-variances as h decreases to zero (Tables 3-5, 3-6, and 3-8). This nonzero variance is called the nugget variance or nugget effect (Journel and Huijbregts, 1978). The nugget effect represents unexplained variance, usually caused by measurement error or microvariability that could not be identified at the scale of sampling used. In this study, the nugget effect gives an indication of the variability that occurs in the field a distances shorter than 10 m. The

Table 3-4. Spatial dependence of selected soil chemical properties from the surface 15 cm of a Lauderhill muck.

Direction†	Intercept‡	Sill	General variance	Range (m)
		pH-H_2O		
Isotropic	-0.0042	0.0592	0.0668	96
N - S	-0.0001	0.0514	0.0668	74
NE - SW	-0.0046	0.0550	0.0668	89
E - W	-0.0102	0.0708	0.0668	118
NW - SE	0.0032	0.0688	0.0668	135
		pH-$CaCl_2$		
Isotropic	-0.0045	0.0017	0.0710	97
N - S	-0.0018	0.0515	0.0710	69
NE - SW	-0.0058	0.0571	0.0710	90
E - W	-0.0127	0.0757	0.0710	118
NW - SE	0.0019	0.0744	0.0710	147
		Log Mehlich I-extractable Mg		
Isotropic	-0.0010	0.0218	0.0218	107
N - S	-0.0014	0.0136	0.0218	60
NE - SW	-0.0020	0.0282	0.0218	120
E - W	-0.0072	0.0326	0.0218	125
NW - SE	0.0021	0.0182	0.0218	122

† Spherical semi-variograms were calculated from 184 observations.
‡ The negative intercepts may be the result of extrapolations of the semi-variograms at distances smaller than 10 m.

Table 3-5. Spatial dependence of selected soil chemical properties from the surface 15 cm of a Pahokee muck.

Direction†	Intercept	Sill	General variance	Range (m)	% of‡ sill
			$pH-H_2O$		
Isotropic	-0.0033	0.0542	0.0607	109	-
N - S	0.0094	0.0349	0.0607	141	27
NE - SW	-0.0028	0.0503	0.0607	117	-
E - W	-0.0133	0.0700	0.0607	114	-
NW - SE	-0.0019	0.0576	0.0607	102	-
			$pH-CaCl_2$		
Isotropic	-0.0054	0.0475	0.0524	106	-
N - S	0.0092	-	0.0524	-	Unbounded
NE - SW	-0.0032	0.0423	0.0524	113	-
E - W	-0.0152	0.0643	0.0524	108	-
NW - SE	-0.0022	0.0521	0.0524	108	-
			Mehlich I-extractable Mn		
Isotropic	2.172	4.522	4.400	102	48
N - S	2.271	3.602	4.400	59	63
NE - SW	2.294	4.531	4.400	93	51
E - W	2.539	5.641	4.400	115	27
NW - SE	2.446	-	4.400	-	Unbounded

† Spherical semi-variograms were calculated from 186 observations.

‡ Percent of sill of semi-variograms with negative intercepts were not calculated. The negative intercepts may be the result of extrapolations of the semi-variogram at distances smaller than 10 m.

Table 3-6. Spatial dependence of selected chemical properties from the surface 15 cm of an Okeelanta muck.

Direction†	Nugget variance	Sill	General variance	Range (m)	% of‡ sill
			$pH-H_2O$		
Isotropic	0.0057	0.0450	0.0443	81	13
N - S	-0.0037	0.0378	0.0443	52	-
NE - SW	0.0074	0.0489	0.0443	103	15
E - W	0.0054	0.0560	0.0443	104	10
NW - SE	0.0013	0.0417	0.0443	64	3
			$pH-CaCl_2$		
Isotropic	-0.0015	0.0433	0.0403	67	-
N - S	-0.0043	0.0357	0.0403	52	-
NE - SW	0.0030	0.0488	0.0403	97	6
E - W	0.0010	0.0541	0.0403	89	2
NW - SE	-0.0053	0.0405	0.0403	52	-
			Log Mehlich I-extractable Fe		
Isotropic	0.0130	0.2810	0.2678	105	5
N - S	-0.0031	0.0169	0.2678	70	-
NE - SW	0.0003	0.3290	0.2678	121	< 1
E - W	-0.0061	0.3610	0.2678	127	-
NW - SE	0.0435	0.1340	0.2678	81	32

† Spherical semi-variograms were calculated from 181 observations.

‡ Percent of sill from semi-variograms with negative intercepts were not calculated. Negative intercepts may be the result of extrapolation of the semi-variograms at distances smaller than 10 m.

Table 3-7. Spatial dependence of selected soil chemical properties of a Lauderhill muck based on isotropic semi-variograms, 0-15 cm.

Variable†	Equation type	Intercept	Sill	Slope	Range (m)	% of sill
	-- Analytical Research Laboratory, Gainesville‡ --					
Log Ca	Spherical	-0.0043	0.0272	-	130	-
Log K	Linear	0.0268	-	0.0007	-	Unbounded
Log P	Linear	0.0180	-	0.0008	-	Unbounded
Log Mn	Spherical	0.0544	0.1027	-	103	53
Log Fe	Spherical	0.0079	0.0636	-	145	12
	---------- Soil Testing Laboratory, EREC§ ---------					
Log P_w	Linear	0.0196	-	0.0011	-	Unbounded
Log P_a	Linear	0.0075	-	0.0006	-	Unbounded
Log K	Linear	0.0246	-	0.0005	-	Unbounded

† Semi-variograms were calculated from 184 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable P), P_a and K (0.5 M acetic acid extractable).

Table 3-8. Spatial dependence of selected soil chemical properties of a Pahokee muck based on isotropic semi-variograms, 0-15 cm.

Variable†	Equation type	Intercept	Sill	Slope	Range (m)	% of sill
	-- Analytical Research Laboratory, Gainesville‡ --					
Log Ca	Spherical	-0.0026	0.0239	-	95	-
Log Mg	Spherical	-0.0010	0.0279	-	127	-
Log K	Linear	0.2550	-	0.0003	-	Unbounded
Log p	Spherical	0.0486	0.1083	-	115	45
Log Zn	Spherical	0.0499	0.0989	-	72	50
Log Cu	No pattern	0.0132	0.0132	-	< 10	100
Log Fe	Spherical	0.0016	0.0180	-	64	9
	---------- Soil Testing Laboratory, EREC§ ---------					
P_w	Spherical	60.97	112.9	-	122	54
Log P_a	Spherical	0.0375	0.0834	-	128	45
Log K	Linear	0.2473	-	0.0003	-	Unbounded
Ca	Spherical	0.0772	0.2604	-	87	30
Log Mg	Spherical	0.0038	0.0215	-	149	18

† Semi-variograms were calculated from 186 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extactable).

Table 3-9. Spatial dependence of selected soil chemical properties of an Okeelanta muck based on isotropic semi-variograms, 0-15 cm.

Variable[†]	Equation type	Intercept	Sill	Slope	Range (m)	% of[¶] sill
	-- Analytical Research Laboratory, Gainesville[‡] --					
Ca	Spherical	-0.3960	3.770	-	103	-
Log Mg	Spherical	-0.0416	0.227	-	84	-
Log K	Spherical	0.0703	0.260	-	157	27
Log P	Spherical	-0.0283	0.545	-	138	-
Zn	Spherical	3.509	18.8	-	115	19
Log Cu	Spherical	0.0356	0.134	-	75	27
Log Mn	Spherical	-0.0670	0.479	-	156	-
	---------- Soil Testing Laboratory, EREC[§] ---------					
Log P_w	Linear	0.0031	-	0.0025	-	Unbounded
Log P_a	Spherical	0.0313	0.183	-	133	17
Log K	Linear	0.0940	-	0.0010	-	Unbounded
Log Ca	Spherical	0.0044	0.859	-	104	< 1
Log Mg	Spherical	0.0044	0.094	-	111	5

† Semi-variograms were calculated from 181 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).
¶ Percent sill from semi-variograms with negative intercepts were not calculated. Negative intercepts may be the result of extrapolation of the semi-variograms at distances smaller than 10 m.

Table 3-10. Spatial dependence of selected chemical properties of a Torry muck based on isotropic semi-variograms, 0-15 cm.

Variable†	Equation type	Nugget variance	Sill	Slope	Range (m)	% of¶ sill
	-- Analytical Research Laboratory, Gainesville‡ --					
pH-H_2O	Spherical	-0.0250	0.1062	-	135	-
pH-$CaCl_2$	Spherical	-0.0285	0.1081	-	129	-
Ca	Linear	0.0710	-	0.0016	-	Unbounded
Log Mg	Spherical	-0.0059	0.0333	-	138	-
K	Linear	0.0076	-	0.0001	-	Unbounded
P	Spherical	52.17	291.7	-	144	18
Zn	Linear	0.3033	-	0.0568	-	Unbounded
Log Cu	Spherical	0.0003	0.0701	-	83	< 1
Log Mn	Spherical	-0.0713	0.4122	-	131	-
Fe	Spherical	0.6979	2.675	-	136	26
	---------- Soil Testing Laboratory, EREC§ ---------					
P_w	Spherical	2.468	39.58	-	131	6
Log P_a	Spherical	-0.0033	0.0445	-	141	-
Log K	Linear	0.0548	-	0.0004	-	Unbounded
Log Ca	Spherical	-0.0154	0.0689	-	151	-
Log Mg	Spherical	-0.0149	0.0699	-	142	-

† Semi-variograms were calculated from 185 observations.

‡ Mehlich I-extractable nutrients.

§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).

¶ Percent of sill from semi-variograms with negative intercepts were not calculated. Negative intercepts may be the result of extrapolation of the semi-variograms at distances smaller than 10 m.

nugget variance can also be expressed as a percentage of the sill (Tables 3-8, 3-9, and 3-10) to compare the relative size of the nugget effect among the chemical properties. Data from those tables show that nugget variances of soil chemical properties from these organic soils range from 0 to 100% of the sill.

Water-pH and pH_s were the only well structured semi-variograms that showed anisotropy (direction-dependency) in the Lauderhill, Pahokee, and Okeelanta mucks (Tables 3-4, 3-5, and 3-6). Mehlich I-extractable Mg, Mn, and Fe also showed anisotropy in the Lauderhill, Pahokee, and Okeelanta mucks, respectively. Semi-variogram structure occurs when there is an increase of the semi-variance to a maximum value. These semi-variograms have distinctive nugget variances (intercept), ranges, and sills (Figs. 3-2, 3-3, 3-4, and 3-5). Other semi-variograms are shown in Appendix B. Anisotropy indicates that the variability of selected soil properties changed with direction. Semi-variograms in the N-S direction (perpendicular to the road) for pH_w, pH_s, and Mg_{MI} and Mn_{MI} from the Lauderhill and Okeelanta mucks showed the shortest range (74, 69, and 60 m, for Lauderhill and 52, 52, and 70 m for Okeelanta, respectively) than the isotropic and the rest of the directional semi-variograms (Tables 3-4 and 3-6). Soil pH_w of samples perpendicular to the road separated by less than 74 m in the Lauderhill muck and less than 52 m in the Okeelanta muck are spatially

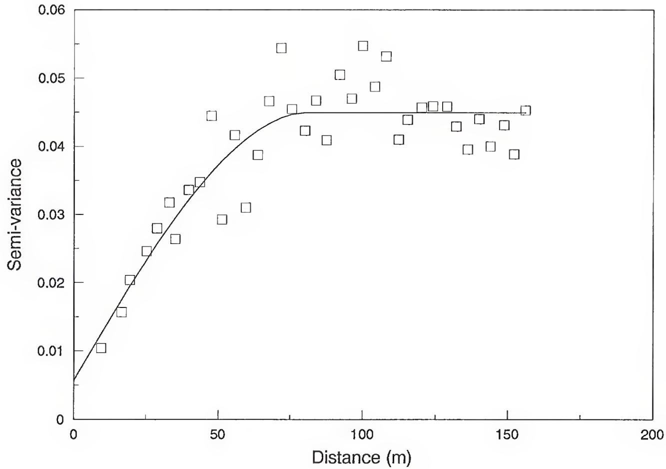

Fig. 3-2. Isotropic semi-variogram of soil pH_w from an Okeelanta muck.

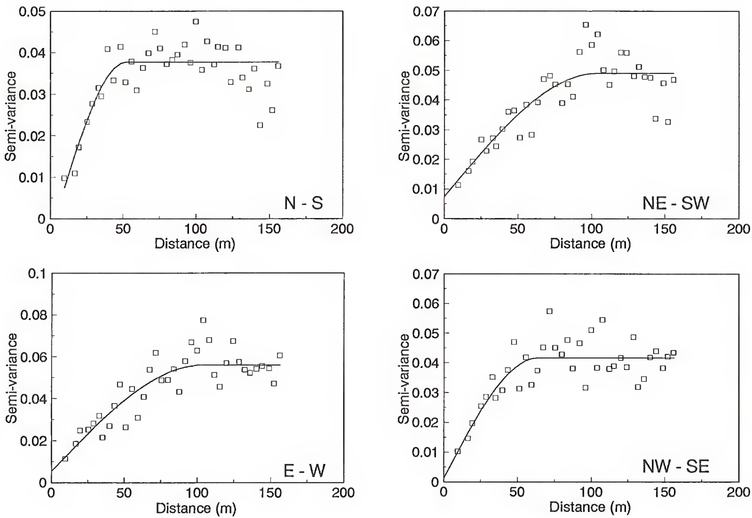

Fig. 3-3. Direction-dependent semi-variograms of soil pH_w from an Okeelanta muck.

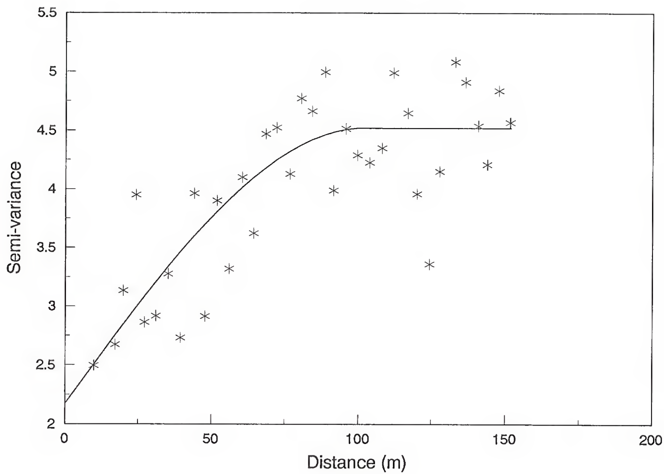

Fig. 3-4. Isotropic semi-variogram of soil Mn_{MI} from a Pahokee muck.

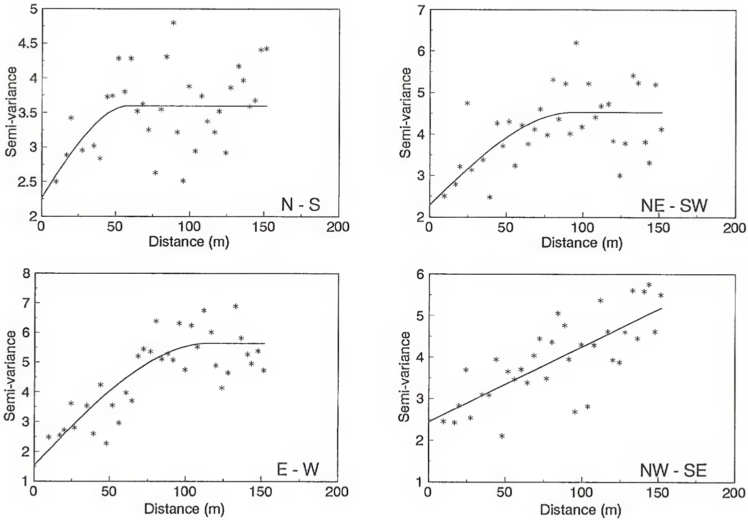

Fig. 3-5. Direction-dependent semi-variograms of soil Mn_{MI} from a Pahokee muck.

dependent, indicating that samples should be separated by at least 74 and 52 m when taken for an unbiased estimate of the average soil pH_w. Semi-variograms in the E-W direction (perpendicular to the ditches) for the same chemical properties showed ranges of 118, 118, and 125 m, for the Lauderhill muck and 104, 89, and 127 m for the Okeelanta muck, respectively.

These results suggest that road spoils have a greater effect than ditch spoils over these chemical properties in these two soils. A network of roads, canals, and ditches is generally constructed to facilitate commercial crop production. The spoils from the marl/limestone bedrock that are dug and spread on the surface during ditch and road construction is one of the main controlling factors affecting the behavior of several soil chemical properties.

Semi-variograms of Mn_{MI} from the Pahokee muck (Table 3-5) showed the largest unexplained variation of all the anisotropic semi-variograms. Semi-variograms in the N-S (perpendicular to the road) and NE-SW directions showed the shortest ranges of spatial influence (59 and 93 m, respectively) and nugget variances that account for 63 and 51% of the sill, respectively. These nugget variances imply that there is more than 50% of unexplained random variance due to measurement errors or spatial variability at distances shorter than 10 m.

Parameters for isotropic (direction-independent) semi-variograms for the four soil series are given on Tables 3-7, 3-8, 3-9, and 3-10, respectively. The range of spatial dependence of P_{MI} ranged from 115 to 144 m, with Pahokee muck showing the shortest range (Fig. 3-6). In contrast, the isotropic semi-variogram for the Lauderhill muck increased unbounded with distance and had no sill. An unbounded semi-variogram means an increase in variation with distance. This kind of semi-variogram indicates the presence of strong directional trends in the property under study (nonstationarity). Water-extractable P, showed well-structured isotropic semi-variograms only for the Pahokee and Torry mucks, with ranges of spatial dependence of 122 and 131 m, respectively (Fig. 3-7). Isotropic semi-variograms for Lauderhill and Okeelanta mucks were unbounded. These results indicate that P_w values from samples taken at distances less than 122 and 131 m from the Pahokee and Torry mucks sites are spatially dependent and will become more alike by reducing the distance between them. In contrast, isotropic semi-variograms from the Lauderhill and Okeelanta mucks are unbounded with distance describing a increasing variation of P_w content across the fields.

Soil K_{MI} and K_a showed unbounded semi-variograms in all soils with the exception of the Okeelanta muck that fitted a spherical model to K_{MI} (Table 3-9). Mehlich I-extractable

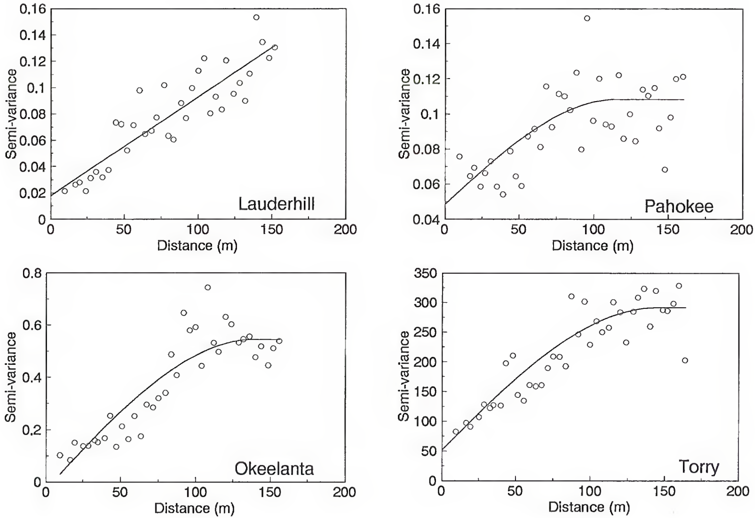

Fig. 3-6. Isotropic semi-variograms of soil P_{MI} of four organic soils from the EAA.

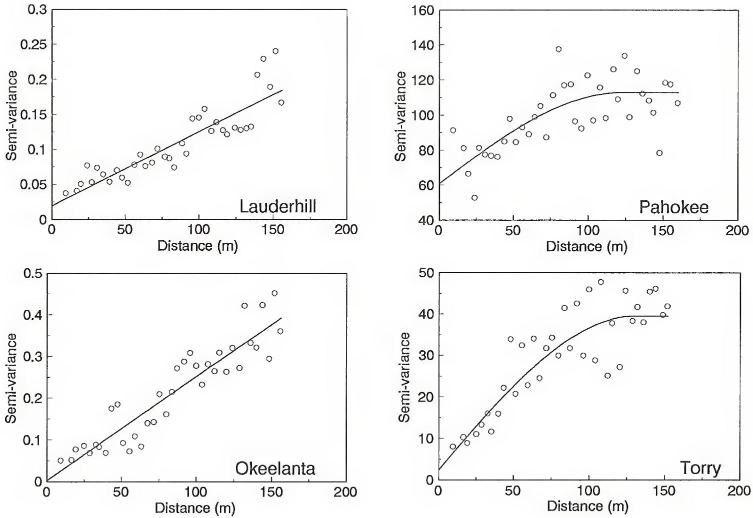

Fig. 3-7. Isotropic semi-variograms of soil P_W of four organic soils from the EAA.

Zn and Cu from the Pahokee muck showed more variation than those from the Okeelanta and Torry mucks (Tables 3-8, 3-9, and 3-10). Soil Zn_{MI} and Cu_{MI} from the Pahokee muck showed ranges of 72 and < 10 m and nugget variances of 50 and 100% of the sill, respectively (Table 3-8). These nugget variances imply that there is 50% measurement errors or short-range variability in the field for Zn and a pure nugget effect for Cu (Fig. 3-8). Pure nugget effect is an indication of a completely random distribution of the variable at the sampling interval used. A well structured semi-variogram with a range and sill may still exist, but samples will have to be taken at shorter distances to detect it.

In contrast, semi-variograms of Zn_{MI} and Cu_{MI} from the Okeelanta and Torry mucks showed larger ranges of spatial influence and smaller nugget variances. Soil Cu_{MI} from the Okeelanta and Torry muck exhibited ranges of 75 and 83 m and nugget variances of 27 and < 1% of the sill. Nugget variance from the Torry muck suggests that there is little measurement error or short range variability in the field for Cu_{MI}.

Zones of spatial dependence shown in the isotropic semi-variograms of Mn_{MI} ranged from 102 m in the Pahokee muck to 156 m in the Okeelanta muck (Tables 3-5 and 3-9). Lauderhill and Pahokee mucks showed the shortest ranges (103 and 102 m, respectively) and the largest nugget variances

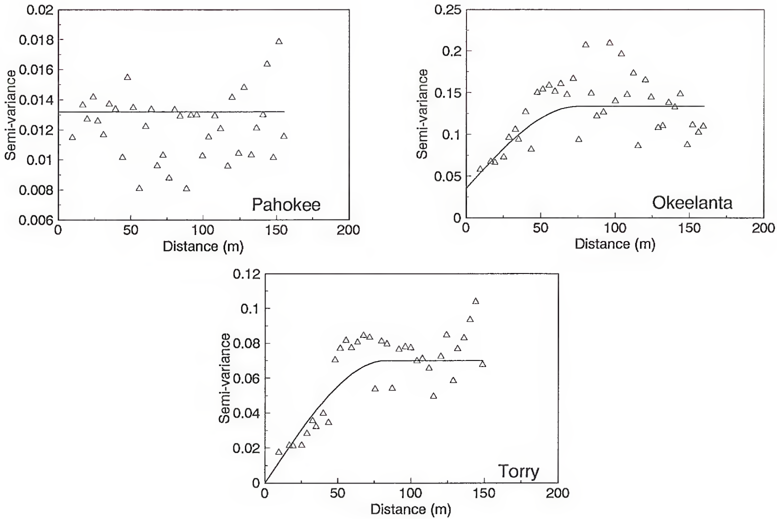

Fig. 3-8. Isotropic semi-variograms of soil Cu_{MI} of three organic soils from the EAA.

(53 and 48%, respectively) (Figs. 3-4 and 3-9). These results agree with the chemical behavior of this element. Lindsay (1972) reported that Mn availability decreases 100 fold for each unit of pH increase. Page (1962) showed that an increase of pH also enhances the production of Mn soil organic matter complexes which also render Mn less available. Therefore, as expected, the isotropic semi-variogram from the Lauderhill and Pahokee mucks showed the largest nugget variance. Although, the overall range of pH_w from the Pahokee muck was not as large as that from the Lauderhill muck (Table 3-3), there were several areas across the field that showed high pH_w values. Mehlich I-extractable Fe yielded well structured semi-variograms with ranges of spatial dependence from 64 to 145 m and nugget variances less than 30% of the sill.

Conclusions

Several of the soil chemical properties studied showed well structured semi-variograms. These results show that selected soil chemical properties from the organic soils of the EAA are spatially dependent. Understanding of changes on soil chemical properties with distance provide valuable information concerning nutrient variability and crop production. This study shows that semi-variograms can be used to detect within-field variability in the organic soils of the EAA. The structure of spatial dependence displayed

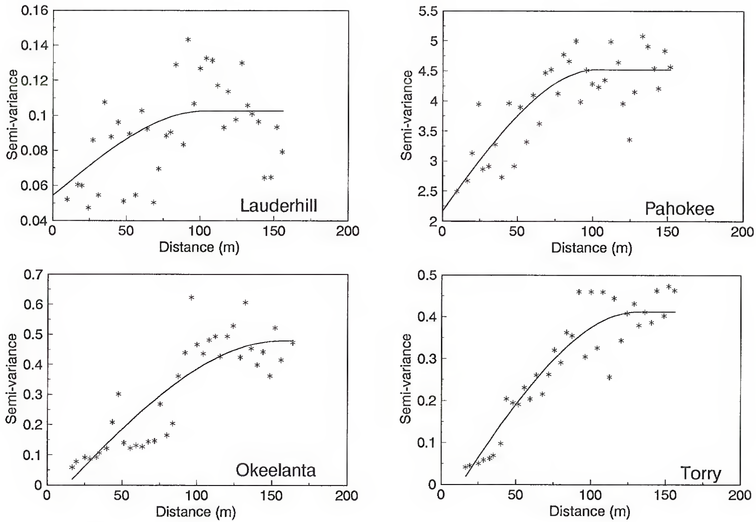

Fig. 3-9. Isotropic semi-variograms of soil Mn_{MI} of four organic soils from the EAA.

by semi-variograms gives information about the direction and range of spatial dependence of the soil chemical properties.

Soil pH, was the only property that showed anisotropic variability in all soils with the exception of Torry muck. Other elements that displayed anisotropy were Mg_{MI}, Mn_{MI}, and Fe_{MI}. Results from the anisotropic semi-variograms showed that road spoils had a greater influence than ditch spoils on these properties as judged by the shorter ranges of spatial dependence. Soil Mn_{MI} from the Pahokee muck was the element exhibiting the highest spatial variability.

Most of the soil properties studied showed isotropic spatial variability. The structure of spatial dependence displayed by the isotropic semi-variograms varied with each soil series. Information from these semi-variograms can contribute to the understanding of soil genesis and behavior of soil properties in the Histosols of the EAA.

The range of spatial dependence of the majority of the soil properties was > 100 m in all locations. These results suggest that samples collected at a distance of 100 m or less are spatially dependent. In contrast, some properties such as P_w, P_a, and K_a from the Lauderhill muck showed a steady increase in soil variability with distance. In general, Torry muck was the most uniform location, while that of the Lauderhill muck was the most variable.

The data obtained from this study provides us with important information about the within-field variability of

these soils that can be used to improve certain management practices. These results helped to identify the soil series as well as the particular chemical properties that exhibited higher variability in the field. With this information we have a better guideline to improve soil-sampling designs for soil testing.

CHAPTER 4
SOIL SPATIAL VARIABILITY OF SELECTED CHEMICAL PROPERTIES IN THE EVERGLADES AGRICULTURAL AREA. II. BLOCK KRIGING

Introduction

The Everglades Agricultural Area (EAA) comprises an area of approximately 313,638 ha of fertile organic soils in south Florida. The EAA was drained at the beginning of the century, and a series of roads and canals were built before the area could be used for the commercial production of winter vegetables and sugarcane. Topographically, the EAA is a relatively uniform area with the majority of its fields being leveled before being put into production. However, the introduction of canals and roads as well as the constant process of soil subsidence added additional sources of soil variability to the area.

Soil spatial variability is a naturally occurring feature that is important in the identification of soil properties relative to soil productivity (Ball et al., 1968; Cline, 1944). Since, soil properties gradually change across the landscape, the investigation of the variability of soil chemical properties with distance has become more important over the past few years. When an observation gives some information as to the value or magnitude of its

neighbor, such data are spatially dependent. When variables are spatially dependent, classical statistical analyses are no longer valid. One method of handling spatially dependent variables is using the theory of regionalized variables (Matheron, 1963). The successful application of this theory to problems in mining, geology, and hydrology led to the more popular name of geostatistics, of which kriging is a main branch (Krige, 1966; Delhomme, 1978).

Kriging is a geostatistical technique of making optimal, unbiased estimates of regionalized variables at unsampled locations using the structural properties of the semi-variogram and the initial set of samples. Kriging is essentially a means of weighted local averages in which the weights are chosen so as to give unbiased estimates while at the same time minimizing the estimation variance. In this sense, kriging is an optimum interpolator (Webster and Burgess, 1983; Webster, 1985). The estimates can be made for points, that is, volumes of soil of the same size and shape as those on which the measurements were made, or for larger blocks of a particular shape. Applications and examples of the use of kriging are extensively discussed by Journel and Huijbregts (1978), Gambolati and Volpi (1979), Vieira et al. (1983), and Trangmar et al. (1985).

In recent years, soil scientists have used kriging to estimate soil parameters (Hajrasuliha et al., 1980; Vieira et al., 1981; Yost et al., 1982b; Xu and Webster, 1984; and

Gaston et al., 1990). Mapping of soil properties is improved by using kriging as a method of estimating soil property values when compared to least-squares estimation techniques (Burgess and Webster, 1980a, 1980b).

The objectives of this study were i) to use geostatistical methods to map spatial variability of soil chemical properties from selected organic soils of the EAA, ii) to use block-kriged contour maps to evaluate the effect of road and ditch spoils on within-field soil variability, and iii) to determine the minimum number of soil samples required for accurately measuring particular soil properties.

Materials and Methods

Soils samples from the upper 15 cm of four different organic soils were used in this study (Table 3-1). Procedures used in the collection, preparation, and laboratory analyses of soil samples are described in Chapter 3.

Statistical Analyses

Mean, range, variance, and coefficient of variation were computed using the Statistical Analysis System (SAS Institute Inc., 1982a, 1982b). The Univariate procedure was used to test for normality. Variables that failed to meet

the normality test were log transformed before geostatistical analysis.

The data from each location were also analyzed to calculate the number of samples needed to obtain a soil value that can satisfy a prescribed margin of error within an acceptable confidence level (α) (Cochran, 1977). Each field (A, B) within a location was separately analyzed to account for variability due to cropping. Data values close to the road and ditch spoils (approximately 40 and 20 m from roads and ditches, respectively) were not used in these analyses. To estimate the number of samples, the overall mean and the sample standard deviation from all soil parameters in each field were calculated. Using these estimates, the number of samples that need to be taken from the field were calculated by the formula

$$n = (t*S)^2/(d)^2 \tag{4-1}$$

$$t = \text{Probability } (1-\alpha/2) \tag{4-2}$$

where n = required number of samples

t = standard normal deviate corresponding to the level of significance α.

S = sample standard deviation

d = sample mean * % relative error

Geostatistical Analyses

Geostatistical approaches applied in this study are based on the theory of regionalized variables, developed originally for mining and mineral exploration (Matheron,

1963). A comprehensive study of geostatistics has been published by David (1977) and Journel and Huijbregts (1978).

Semi-variograms

The principal tool of geostatistics in the analysis of spatially dependent data is the semi-variogram. Semi-variograms were computed using the program VAR5, Version 2.0, which is a part of a geostatistical package developed by the University of Hawaii (Yost et al., 1989). Semi-variograms were calculated from the formula

$$\Gamma(h) = 1/2N\ (h)\ \Sigma\ [Y(x) - Y(x+h)]^2 \qquad (4\text{-}3)$$

where N is the number of sample pairs at each distance interval (h), and Y(x) and Y(x+h) are random variables corresponding to sites separated by a distance h. Semi-variograms were averaged over 180 degrees (direction independent) and over 90 degrees in four directions (N-S, NE-SW, E-W, and NW-SE) to test for anisotropy (direction dependent). Weighted least square methods as implemented in SAS nonlinear procedures were used to model linear and spherical semi-variograms.

Block Kriging

Once appropriate semi-variograms were determined, interpolations were made by block kriging (Yost et al., 1989). Kriging is the second major tool of geostatistics. In this method, the kriged estimate of a property $Z(X_0)$, at a location X_0 is the weighed average of the values

$$\hat{Z}(_0) = \sum_{i=1}^{n} f_i Z(X_i) \quad (4\text{-}4)$$

where n is the number of neighboring samples $Z(X_i)$ and f_i are weights applied to each $Z(X_i)$. The weights are chosen so that (i) they sum to 1, thereby assuring lack of bias, and (ii) the estimation variance is minimized

$$E[\hat{Z}(X_0)-Z(X_0)] = 0 \quad (4\text{-}5)$$

$$\sigma^2_k = VAR[\hat{Z}(X_0)-Z(X_0)] = \text{minimum} \quad (4\text{-}6)$$

One of the main advantages of kriging over other interpolation mapping methods is that it provides the interpolation error estimates, which can be used to build reliability maps. Contour maps of selected chemical properties from each location were made using the program SURFER Version 4. To make the contour maps, 340 kriged values for each soil parameter were estimated in blocks 20 x 20 m at intervals of 20 m.

Results and Discussion

Spatial Analysis

Despite uniform field topography in the EAA, there was marked soil heterogeneity among the soil series studied. Description of the soil series and related crops, and sampling pattern used in this study are given in Tables 3-1 and 3-2 and Fig. 3-1, respectively. One of the main objectives of this study was to measure the influence of

road and canal spoils on soil variability. To accomplish that objective, calculation of semi-variograms was based only on the large sampling pattern (14 ha area, 100 samples), including all samples close to the road and canals. The small sampling pattern was not used in these analyses due to limitations in the kriging program regarding the maximum number of neighboring points the program could handle.

Calculated semi-variograms did not indicate direction dependency as those shown by semi-variograms of some chemical properties in Chapter 3. Isotropic semi-variograms from each soil series and chemical property are shown in Tables 4-1 to 4-4. For the majority of soil chemical properties analyzed, the model that fit the semi-variances best was the linear semi-variogram, with moderate gradient and large intercepts. Spherical semi-variograms were also fitted to some chemical properties, especially in the Torry muck (Table 4-4). The presence of large nugget variances (intercepts) indicated that a large percentage of the soil spatial variability was not detected at the smaller lag distance used (43 m). Thus, more sampling would be needed to calculate more reliable semi-variograms.

Block-kriging and Mapping

Using the structural information derived from the fitted semi-variograms (Tables 4-1 to 4-4), values of

Table 4-1. Effect of road and ditch spoils on the spatial dependence of selected soil chemical properties from the surface 15 cm of a Lauderhill muck.

Soil property	Equation† type	Nugget variance	Sill	Slope	Range (m)
	- Analytical Research Laboratory, Gainesville‡ -				
pH-H_2O	Linear	0.0309	-	0.00097	-
pH-$CaCl_2$	Linear	0.0312	-	0.00095	-
Log Ca	Linear	0.0042	-	0.00021	-
Log Mg	Linear	0.0184	-	0.00011	-
Log K	Spherical	0.0351	0.1542	-	144
Log P	Linear	0.0936	-	0.00083	-
Log Zn	Linear	0.1630	-	0.00067	-
Log Cu	Linear	0.0426	-	0.00208	-
Mn	Spherical	0.0359	0.0843	-	138
Log Fe	Linear	0.0131	-	0.00070	-
	-------- Soil Testing Laboratory, EREC§ ---------				
Log P_w	Spherical	0.0551	0.2296	-	135
Log P_a	Spherical	0.0171	0.1198	-	137
Log K	Spherical	0.0325	0.1259	-	129
Ca	Linear	0.1844	-	0.00113	-
Log Mg	Linear	0.0061	-	0.00002	-
Log P_w/P_a	Linear	0.0682	-	0.00057	-

† Isotropic semi-variograms were calculated from 100 observations.

‡ Mehlich I-extractable nutrients.

§ P_w (water-extractable), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).

Table 4-2. Effect of road and ditch spoils on the spatial dependence of selected soil chemical properties from the surface 15 cm of a Pahokee muck.

Soil property	Equation† type	Nugget variance	Sill	Slope	Range (m)
	-- Analytical Research Laboratory, Gainesville‡ -				
pH-H_2O	Linear	0.1291	-	0.00092	-
pH-$CaCl_2$	Linear	0.1322	-	0.00095	-
Ca	Spherical	0.7722	1.450	-	105
Mg	Linear	0.0323	-	0.00004	-
Log K	Linear	0.2281	-	0.00030	-
Log P	Spherical	0.0279	0.1618	-	129
Log Zn	Linear	0.1900	-	0.00037	-
Log Cu	Spherical	0.0026	0.0118	-	122
Mn	Linear	4.899	-	0.01674	-
Log Fe	Linear	0.0539	-	0.00004	-
	--------- Soil Testing Laboratory, EREC§ --------				
P_w	Spherical	46.32	103.55	-	127
Log P_a	Linear	0.0308	-	0.00101	-
Log K	Linear	0.1979	-	0.00034	-
Ca	Spherical	0.1997	0.3281	-	116
Log Mg	Linear	0.0145	-	0.00004	-
Log P_w/P_a	Linear	0.0375	-	0.00124	-

† Isotropic semi-variograms were calculated from 100 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).

Table 4-3. Effect of road and ditch spoils on the spatial dependence of selected soil chemical properties from the surface 15 cm of an Okeelanta muck.

Soil property†	Nugget variance	Slope
-- Analytical Research Laboratory, Gainesville‡ --		
pH-H_2O	0.5035	0.00270
pH-$CaCl_2$	0.5239	0.00244
Ca	2.673	0.01361
Log Mg	0.1431	0.00179
Log K	0.2660	0.00096
Log P	0.5510	0.00263
Log Zn	0.9667	0.00408
Log Cu	0.0865	0.00030
Log Mn	0.7142	0.00410
Log Fe	0.5123	0.00208
--------- Soil Testing Laboratory, EREC§ ---------		
Log P_w	0.3640	0.00209
Log P_a	0.0665	0.00099
K	0.2507	0.00071
Ca	0.5134	0.00397
Mg	0.0455	0.00038
P_w/P_a	0.0403	0.00010

† Linear isotropic semi-variograms were calculated from 100 observations.

‡ Mehlich I-extractable nutrients.

§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).

Table 4-4. Effect of road and ditch spoils on the spatial dependence of selected soil chemical properties from the surface 15 cm of a Torry muck.

Soil property	Equation[†] type	Nugget variance	Sill	Slope	Range (m)
	- Analytical Research Laboratory, Gainesville[‡] --				
pH-H_2O	Linear	0.1404	-	0.00188	-
pH-$CaCl_2$	Linear	0.1633	-	0.00189	-
Ca	Spherical	0.0006	0.4601	-	136
Log Mg	Spherical	0.0060	0.0475	-	124
Log K	Linear	0.0751	-	0.00040	-
Log P	Spherical	0.0749	0.2061	-	151
Zn	Linear	4.621	-	0.06944	-
Log Cu	Spherical	0.0073	0.0401	-	156
Log Mn	Linear	0.2143	-	0.00488	-
Log Fe	Linear	0.1176	-	0.00125	-
	-------- Soil Testing Laboratory, EREC[§] ---------				
Log P_w	Spherical	0.0294	0.1484	-	124
Log P_a	Linear	0.0162	-	0.00022	-
Log K	Spherical	0.0860	0.1679	-	128
Ca	Spherical	0.0086	1.126	-	142
Log Mg	Spherical	0.0077	0.1202	-	140
Log P_w/P_a	Spherical	0.0375	0.1965	-	141

† Isotropic semi-variograms were calculated from 100 observations.

‡ Mehlich I-extractable nutrients.

§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid ectractable).

selected chemical properties were interpolated at 340 locations using block-kriging. Interpolated values were used to produce contour maps of selected chemical properties. Contour maps of pH_w from each soil series are shown in Fig. 4-1. Soil pH_w is relative uniform within the fields, with most of the variability occurring close to the roads and ditches. Lauderhill muck was the only soil that showed some variability within the field, probably due to the fact that these are shallow soils with limestone bedrock close to the surface. However, the effect of a marl/limestone ditch and road spoils on pH_w variability is evident in all soils. Visual analysis of pH_w contour maps indicates that road spoils significantly affect a strip of soil approximately 40 to 50 m wide (Fig. 4-1). Soil variability due to ditches is not as obvious as the road spoil effect. Ditch spoils varies from location to location due to the different ditch management practices at each farm. A common practice in the EAA that increases soil variability due to ditches is the regular cleaning of ditches and canals, and the subsequent dumping and spread of the spoils to one side of the field. Contour maps of the Okeelanta and Torry mucks show this effect on the lefthand side of the middle ditches (field A) and close to the ditch on the righthand side of the Torry muck (field B). Soil pH_w variability displayed by the Lauderhill muck in the middle ditch is due by a combination of road and ditch spoils.

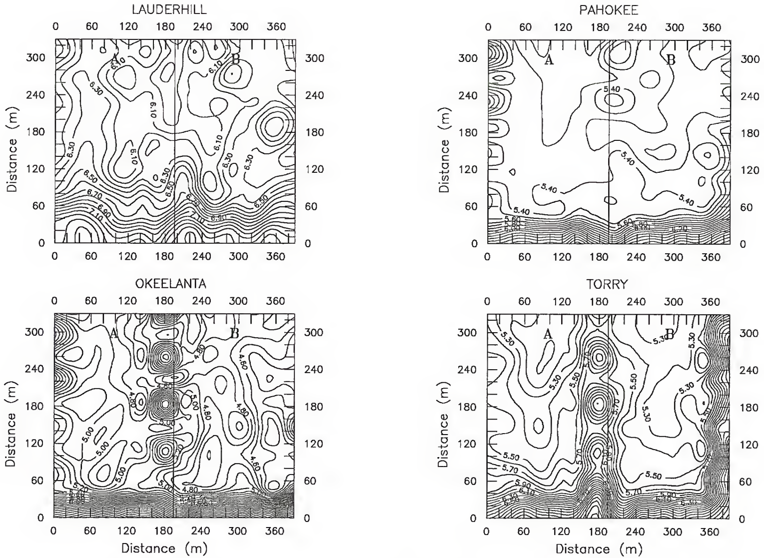

Fig. 4-1. Contour maps of soil pH_w from four organic soils of the EAA estimated by block kriging.

Visual analysis of these contour maps suggests that an area at least 40 to 50 m from the road and 25 to 30 m on either side of the ditches should be avoided when samples are taken to test the pH_w of these fields.

Contour maps of P_w (Fig. 4-2) showed also P variability throughout the field due to road and ditch effect, but not as dramatic as the variability shown by P_{MI} (Fig. 4-3) and P_a (Fig. 4-4). Water-extractable P concentrations from the Okeelanta muck varied from about 60 and 20 mg kg^{-1} from the middle of fields A and B, to about 10 mg kg^{-1} in the areas close to the road. Similar results were observed in the other three soils (Fig. 4-2). The drastic decrease in P_w close to the road is due to the presence of high concentrations of free carbonates (Griffin and Jurinak, 1973; Anderson, 1990b). Effects due to ditches were observed only in the Okeelanta and Torry mucks. These results agree with the pH_w contour maps (Fig. 4-1) that showed more variability due to ditches in the same two soils.

These maps are also helpful in showing P variability due to previous cropping or crops at the time of sampling. Fields A and B from the Lauderhill muck had a history of sugarcane production, but at the time of sampling, field A was in fallow and field B was in sod production. The contour map from this location shows that field B exhibited P_w values twice as high as those from field A. Generally,

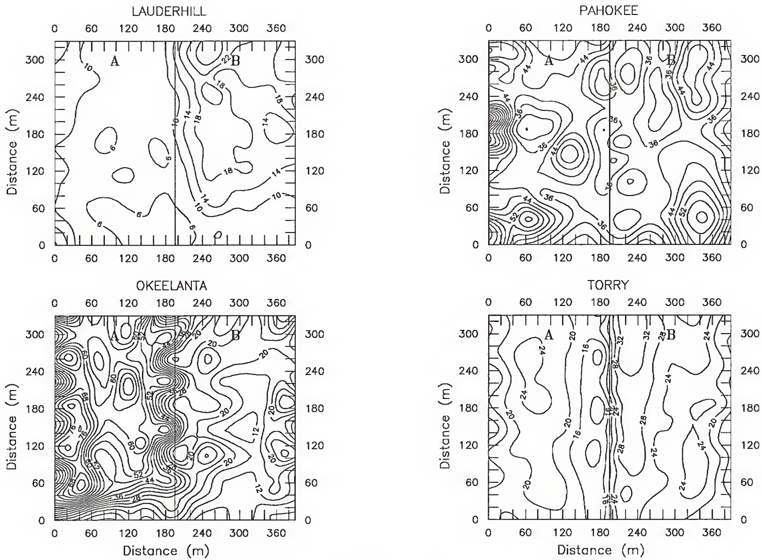

Fig. 4-2. Contour maps of P_w (mg kg^{-1}) from four organic soils of the EAA estimated by block kriging.

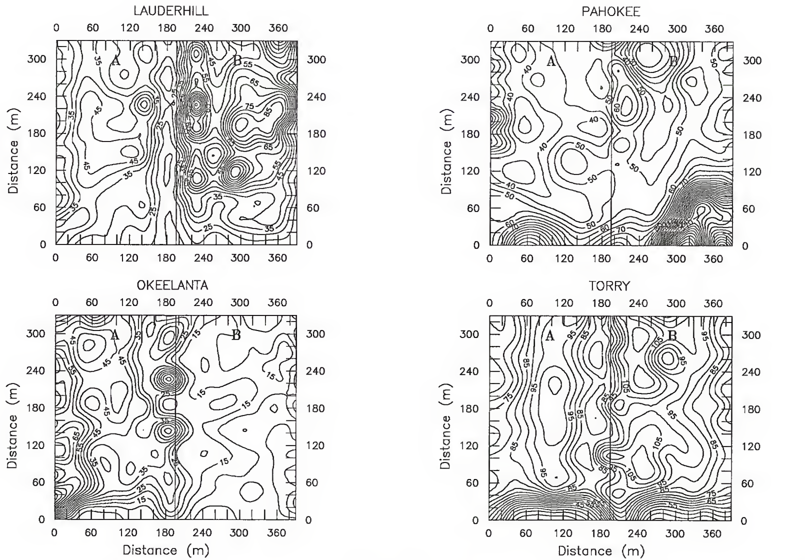

Fig. 4-3. Contour maps of P_{MI} (mg kg^{-1}) from four organic soils of the EAA estimated by block kriging.

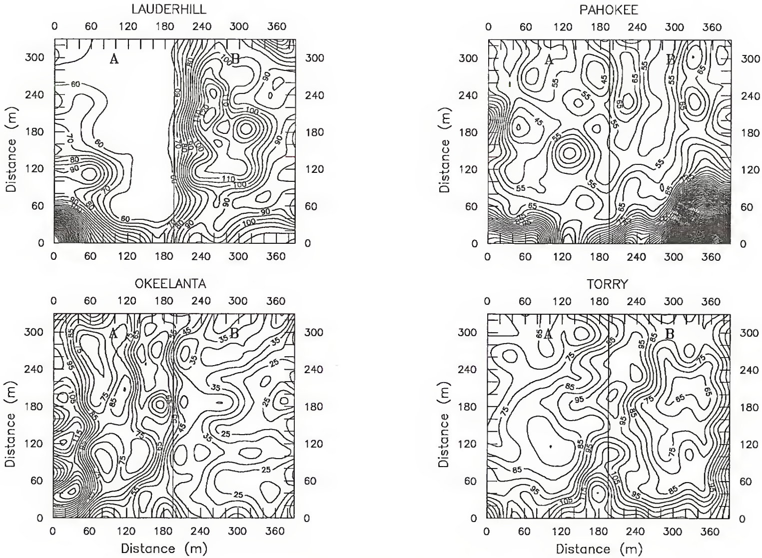

Fig. 4-4. Contour maps of P_a (mg kg^{-1}) from four organic soils of the EAA estimated by block kriging.

sod production requires more P (approximately 50 kg P ha^{-1} yr^{-1}) than sugarcane production (15 to 40 kg P ha^{-1} yr^{-1}) in organic soil (Anderson, 1987; Anderson, 1990a).

Fields from the Okeelanta location had a similar situation. Both fields from this location were fallow, however, field A was previously in sweetcorn production (harvested 1 wk before sampling), while field B was previously in sugarcane production (fallow during summer). Results from this location show P_W concentrations from field A to be three-times higher than those shown in field B. Usually, P application for sweetcorn production in organic soils is more intensive (70 to 80 kg P ha^{-1} yr^{-1}) than for sugarcane production.

Contour maps from P_{MI} showed high variability due to roads, ditches, and cropping (Fig. 4-3). Soil P_{MI} concentrations from the Lauderhill muck varied from about 45 and 65 mg P kg^{-1} across the middle of fields A and B, respectively, to approximately 20 mg P kg^{-1} to the areas adjacent to the road and approximately 25 mg P kg^{-1} to the areas adjacent to ditches. Similar variability patterns are shown by the Okeelanta and Torry mucks. Soil P_{MI} values from the Pahokee muck were uniform with the exception of areas adjacent to the road and ditches. This location shows P_{MI} concentrations as high as 200 mg kg^{-1} in the lower right-hand of field B. This corner is a filled area that was probably used as a loading platform for machinery.

Soil P_a contour maps showed similar variability patterns as those shown by P_{MI} (Fig. 4-4). Soil P_a showed high variability due to roads, ditches, and cropping. Soil P_a variability due to the road and the equipment loading area in the Pahokee muck is prominent. These areas showed unusual high P_a (> 200 mg P kg^{-1}) compared to the rest of the field. Soil P_{MI} and P_a variability due to cropping were also evident. Average soil P_{MI} and P_a values from field B (sod production) of Lauderhill muck were approximately twice as high as those measured in field B (sugarcane fallow). Similarly, soil P_{MI} and P_a from field A (sweetcorn fallow) of the Okeelanta muck were approximately twice as high as the concentrations measured in field B (sugarcane fallow).

The effect of road and ditch spoils on P availability is clearly shown in the contour maps of the ratio P_w/P_a (Fig. 4-5). The P_w/P_a ratios across field A of the Okeelanta muck decreased from 0.80 to 0.24 and 0.40 in the areas adjacent to the road and ditches, respectively. Similar variability patterns were shown by the other three soils. Low P_w/P_a ratios close to roads and ditches are due to low P_w and high P_a concentrations in those areas as a result of the presence of high concentrations of free-carbonates (Griffin and Jurinak, 1973; Anderson, 1990b). With the continuous process of soil subsidence in the EAA, larger areas will be affected by the limestone bedrock,

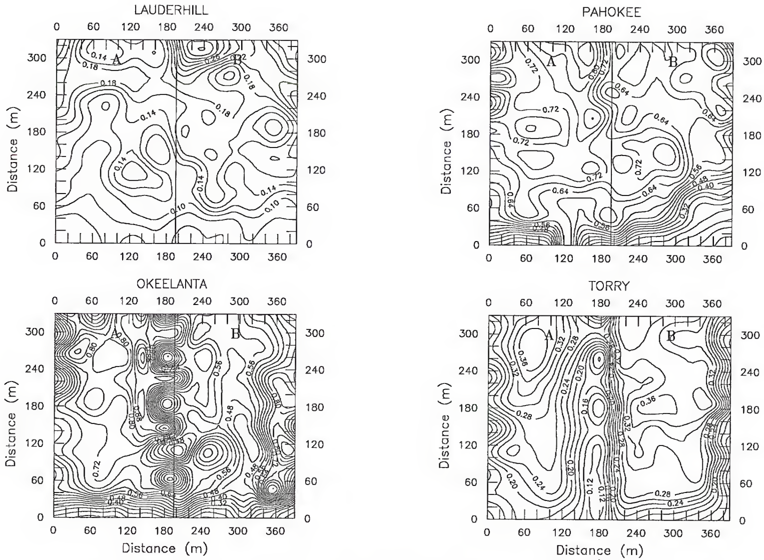

Fig. 4-5. Contour maps of P_w/P_a from four organic soils of the EAA estimated by block kriging.

increasing sorption and precipitation of P by exchangeable Ca or $CaCO_3$.

These contour maps (Figs. 4-2 to 4-5) show valuable information regarding P variability in the field. These maps identify those areas that should be avoided at the time of sampling. Visual analysis of the contour maps suggests that an area about 40 to 50 m from the road and 25 to 30 m from each side of the ditches should be avoided when sampling for P recommendations.

Contour maps were also useful to show the spatial variability of micronutrients in these organic soils. Contour maps of Mn_{MI}, Fe_{MI} and Cu_{MI} are shown in Figs. 4-6, 4-7, and 4-8, respectively. All micronutrients were affected by soil pH at all locations. Soil Mn_{MI} concentrations were reduced from two to ten times in areas adjacent to roads and ditches at all locations (Fig. 4-6). Torry muck was the soil that showed the highest Mn_{MI} variability. Soil Mn_{MI} concentrations in this soil ranged from 22 and 38 mg kg^{-1} in the middle of fields A and B, respectively, to 4 and 10 mg kg^{-1} in areas adjacent to the road and ditches, respectively. Similarly, Fe_{MI} (Fig. 4-7) and Cu_{MI} (Fig. 4-8) availability were affected by high soil pH found in areas adjacent to roads and ditches. Okeelanta and Torry mucks showed the highest Fe and Cu variability. Soil Fe_{MI} concentrations from the Okeelanta muck varied from about 16 mg kg^{-1} in the middle of the fields to about 2 mg

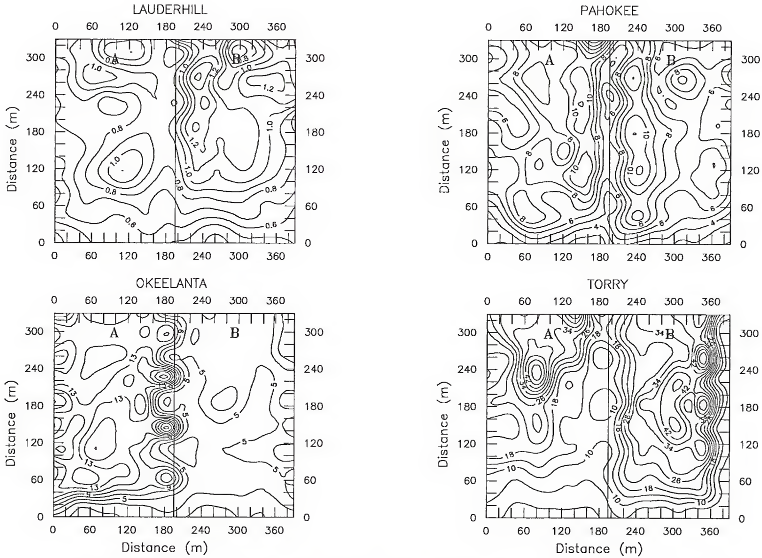

Fig. 4-6. Contour maps of Mn_{MI} (mg kg^{-1}) from four organic soils of the EAA estimated by block kriging.

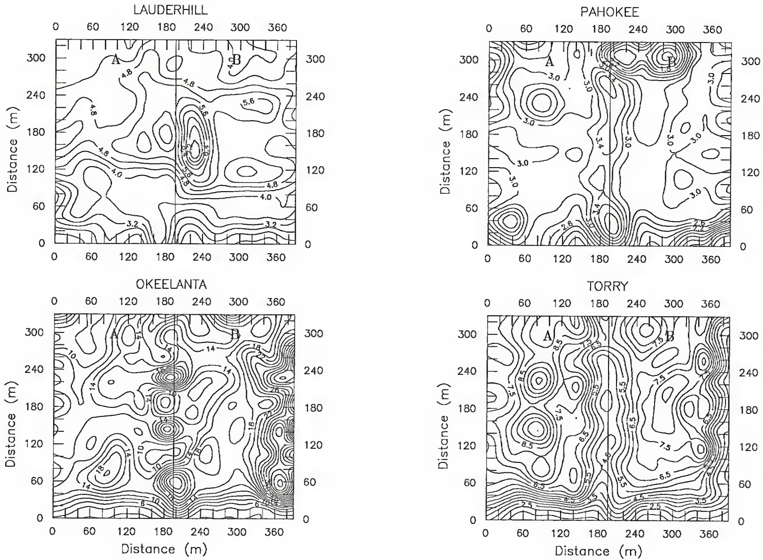

Fig. 4-7. Contour maps of Fe_{MI} (mg kg^{-1}) from four organic soils of the EAA estimated by block kriging.

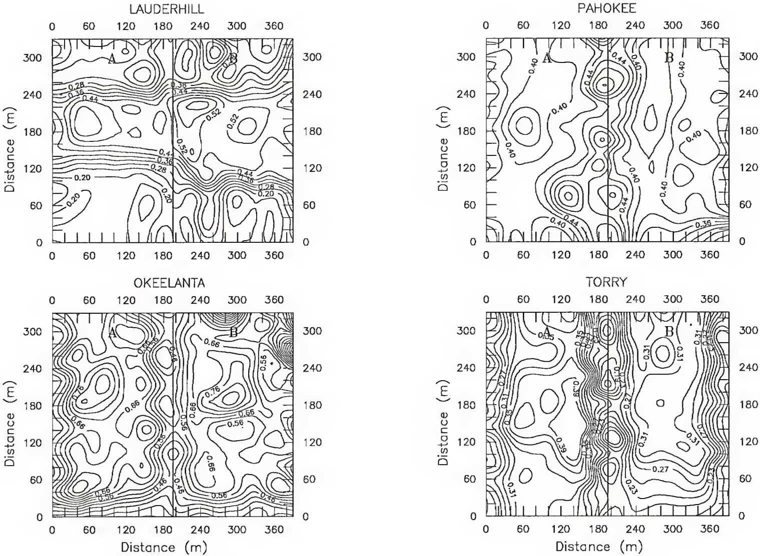

Fig. 4-8. Contour maps of Cu_{MI} (mg kg^{-1}) from four organic soils of the EAA estimated by block kriging.

kg^{-1} close to the road. Similar variability patterns were shown by contour maps of Cu_{MI} (Fig. 4-8). At all locations, low and high Fe and Cu concentrations corresponded to areas with high or low pHw, respectively.

Soil Sampling

Determination of the number of samples needed to give reproducible soil-test results is of practical significance. Data from the semi-variograms and visual analysis of the contour maps identified road and ditch spoils as the main factors influencing within-field soil variability. Based on these findings, soil data from the middle of each field were used to calculate the number of samples required to satisfy 5 to 20% margin of error from the overall mean at the 90 and 95% confidence levels (Tables 4-5, 4-6, 4-7, and 4-8).

Soil pH_w was one of most uniform soil chemical properties in the middle of the fields as judged by the contour maps (Fig. 4-1), low CV (< 7%), and the low number of samples required to generate values of acceptable confidence (Tables 4-5 to 4-8). According to the results, four to six soil samples are required to generate a pH_w value with a 5% margin error at the 90% confidence level.

Soil Mg was also relatively uniform in all soils with the exception of Mg_{MI} from the Okeelanta muck and Mg_a from the Torry muck. The minimum number of samples required to produce a Mg value within 10% of the population mean at the

Table 4-5. Sample sizes required for estimating the true mean (μ) for selected chemical properties in a Lauderhill muck.

Soil property[†]	Confidence level (%)						Confidence level (%)					
	90			95			90			95		
	Relative error (%)						Relative error (%)					
	5	10	20	5	10	20	5	10	20	5	10	20
	Field A, Sugarcane-Fallow						Field B, Sod					
	Analytical Research Laboratory, Gainesville[‡]											
$pH-H_2O$	4	1	1	5	1	1	3	1	1	4	1	1
Mg	30	7	2	42	11	3	15	4	1	21	5	1
K	79	20	5	111	28	7	101	25	6	144	36	9
P	113	28	7	161	40	10	135	34	9	192	48	12
Mn	85	21	5	121	30	8	75	19	5	106	27	7
Fe	36	9	2	51	13	3	48	12	3	68	17	4
	Soil Testing Laboratory, EREC[§]											
P_w	135	34	9	192	48	12	130	33	8	185	46	12
P_a	127	32	8	181	45	11	48	12	3	69	17	4
K	61	15	4	87	22	6	91	23	6	129	32	8
Mg	5	1	1	8	2	1	5	1	1	7	2	1

† Calculations were based on 115 observations.
‡ Mehlich I-extractable nutrients.
§ Water extractable P (P_w), 0.5 M acetic acid extractable-nutrients (P_a, K, and Mg).

Table 4-6. Sample sizes required for estimating the true mean (μ) for selected chemical properties in a Pahokee muck.

Soil property†	Confidence level (%)						Confidence level (%)					
	90			95			90			95		
	Relative error (%)						Relative error (%)					
	5	10	20	5	10	20	5	10	20	5	10	20
	Field A, Sugarcane						Field B, Sugarcane					
	Analytical Research Laboratory, Gainesville‡											
pH-H_2O	3	1	1	4	1	1	2	1	1	2	1	1
Mg	16	4	2	23	6	2	21	5	1	30	7	2
K	368	92	23	523	131	33	259	65	16	367	92	23
P	124	31	8	176	44	11	212	53	13	301	75	19
Zn	122	30	8	173	43	11	154	39	10	218	55	14
Cu	15	4	1	22	6	2	15	4	1	21	5	1
Mn	123	31	8	175	44	11	91	23	6	130	32	8
Fe	29	7	2	42	10	3	31	8	2	44	11	3
	Soil Testing Taboratory, EREC§											
P_w	138	34	9	195	49	12	69	17	4	99	25	6
P_a	143	36	9	203	51	13	253	63	16	359	90	23
K	390	97	24	553	138	35	286	72	18	406	102	25
Mg	18	5	1	25	6	2	20	5	1	29	7	2

† Calculations were based on 115 observations.
‡ Mehlich I-extractable nutrients.
§ Water extractable P (P_w), 0.5 M acetic acid extractable-nutrients (Pa, K, and Mg).

Table 4-7. Sample sizes required for estimating the true mean (μ) for selected chemical properties in an Okeelanta muck.

Soil property†	Confidence level (%)						Confidence level (%)					
	90			95			90			95		
	Relative error (%)						Relative error (%)					
	5	10	20	5	10	20	5	10	20	5	10	20
	Field A, Sweetcorn-Fallow						Field B, Sugarcane-Fallow					
	Analytical Research Laboratory, Gainesville‡											
pH-H_2O	6	2	1	8	2	1	2	1	1	3	1	1
Mg	474	119	30	673	168	42	142	35	9	201	50	13
K	125	31	8	177	44	11	291	73	18	413	103	26
P	198	50	12	281	70	18	263	66	16	373	93	23
Zn	119	30	8	169	42	11	225	56	14	319	80	20
Cu	125	31	8	177	44	11	180	45	11	255	64	16
Mn	140	35	9	198	50	12	209	52	13	297	74	19
Fe	178	44	11	252	63	16	242	60	15	343	86	22
	Soil Testing Laboratory, EREC§											
P_w	80	20	5	113	28	7	190	48	12	270	68	17
P_a	125	31	8	177	44	11	129	32	8	182	46	11
K	126	32	8	179	45	11	271	68	17	184	96	24
Mg	27	7	2	38	10	3	107	27	7	152	38	10

† Calculations were based on 115 observations.
‡ Mehlich I-extractable nutrients.
§ Water extractable P (P_w), 0.5 M acetic acid extractable-nutrients (P_a, K, and Mg).

Table 4-8. Sample sizes required for estimating the true mean (μ) for selected chemical properties in a Torry muck.

Soil property†	Confidence level (%)						Confidence level (%)					
	90			95			90			95		
	Relative error (%)						Relative error (%)					
	5	10	20	5	10	20	5	10	20	5	10	20
	Field A, Sugarcane						Field B, Sweetcorn-Fallow					
	Analytical Research Laboratory, Gainesville‡											
$pH-H_2O$	5	1	1	7	2	1	6	1	1	8	2	1
Mg	46	11	3	65	16	4	19	5	1	27	7	2
K	71	18	5	101	25	6	56	14	4	79	20	5
P	29	7	2	41	10	3	31	8	2	45	11	3
Zn	44	11	3	63	16	4	91	23	6	129	32	8
Cu	120	30	8	171	43	11	85	21	5	121	30	8
Mn	360	90	23	511	128	32	191	48	12	271	68	17
Fe	64	16	4	90	23	6	69	17	4	98	24	6
	Soil Testing Laboratory, EREC§											
P_w	106	27	7	150	38	9	37	9	2	53	13	3
P_a	46	12	3	66	16	4	33	8	2	47	12	3
K	111	28	7	157	39	10	76	19	5	108	27	7
Mg	130	33	8	185	46	12	65	16	4	93	23	6

† Calculations were based on 115 observations.
‡ Mehlich I-extractable nutrients.
§ Water extractable P (P_w), 0.5 M acetic acid extractable-nutrients (P_a, K, and Mg).

90% confidence level is 10 to 15. However, Mg_{Mi} from the Okeelanta muck and Mg_a from the Torry muck required > 35 and 16 samples, respectively.

Potassium was one of the major elements requiring a large number of samples to obtain reliable estimates. Potassium (K_{MI} and K_a) variability among fields is substantial as shown by the number of samples required to obtain credible estimates (Tables 4-5 to 4-8). Pahokee muck (CV > 50%) showed the highest K variability, while Torry muck (CV < 30%) showed the lowest K variability. The large number of samples required for K indicates that a good sampling for this element in the EAA is very difficult. A practical number of samples for K can be 15 to 20 to produce values within 20% of the population mean at the 90% confidence level.

Phosphorus variability among soil series studied was considerable. Water-extractable P values showed on the average higher variability than P_a. Torry muck was the least variable soil requiring an average of 18 samples to produce a P_w value within 10% of the population mean at the 90% confidence level. In contrast, field B from the Okeelanta muck showed the highest variability, requiring a minimum of 48 samples to produce an acceptable P_w value.

Mehlich I-extractable P and P_a variability were greater in the Pahokee and Okeelanta mucks (Tables 4-6 and 4-7, respectively). The Okeelanta site required an average of 58

samples, while the Pahokee site required an average of 50 samples to produce P_{MI} and P_a values within 10% of the population mean with 90% confidence level, respectively. In contrast, Torry muck was the least variable location, requiring an average of eight to 10 samples to produce reliable P_{MI} and P_a values (Table 4-8). Torry mucks are deeper soils with a higher total P content than the rest of the organic soils of the EAA. In contrast, the Okeelanta muck had a highly irregular organic layer with several spots in the field mixed with the sandy layer that is usually located underneath this soil series. Similarly, field B from the Pahokee site had a quite large area used for loading of field equipment that yielded P_a values two and three times higher than the rest of the field (CV 48%) (Fig. 4-4).

Cropping history affected the minimum number of samples required for a particular element. However, cropping effect differed with location and extractant solution, as shown by the number of samples required for Mg, K, and P (Tables 4-5, 4-7, and 4-8). The Okeelanta muck showed the highest Mg variability due to cropping, however, variability in the Lauderhill and Torry mucks was also evident. Torry and Okeelanta mucks showed a significant P_w variability due to cropping (Tables 4-7 and 4-8, respectively). The sugarcane-fallow field (B) from the Okeelanta muck, requires a minimum of 48 samples (CV 42%), while the sweetcorn-fallow field (A)

requires 20 samples (CV 27%) to produce a P_W value within 10% from the population mean at the 90% confidence level (Table 4-7). Similarly, the fallow field (B) from the Torry muck, requires only nine samples (CV 19%), compared to 27 samples from sugarcane field (A) (CV 31%) (Table 4-8).

Micronutrient variability among soil series was considerable. Mehlich I-extractable Mn was the micronutrient that required the largest number of samples in most of the soils studied. Torry muck, showed the highest Mn_{MI} variability, requiring 90 and 48 samples to produce a value within 10% of the population mean at the 90% confidence level (Table 4-8). However, the Okeelanta muck was the location requiring the largest number of samples to produce a reliable Zn_{MI}, Cu_{MI}, and Fe_{MI} value (Table 4-7). Cropping history also influenced the number of samples required for micronutrients (Tables 4-7 and 4-8).

Conclusions

Kriging is a valuable technique that can be applied to many problems in agriculture in which the responsive variable is spatially dependent. Results from this study showed that selected chemical properties from the Histosols of the EAA are spatially dependent. Kriged-contour maps proved to be a valuable technique to evaluate the spatial variability occurring in Histosols of the EAA. Contour maps identified the influence of $CaCO_3$ in road and ditch spoils

as some of the main factors influencing field-soil variability. Depth of the organic layer to the bedrock is also an important factor affecting soil variability. Soil depth is a factor that will play a major role in soil variability in the future, as these fields subside with time. Visual analysis from contour maps suggested that an area approximately 40 to 50 m from the road and 25 to 30 m from each side of the ditches should be avoided during soil sampling.

Kriging was also useful in mapping soil variability due to cropping history. Contour maps from the Okeelanta and Lauderhill mucks showed large differences in P concentrations due to cropping (Figs. 4-2 through 4-4). Phosphorus concentrations in the sweetcorn-fallow field (A) from the Okeelanta muck were twice as high as the P concentrations from the sugarcane-fallow field (B). Similarly, P concentrations from the sod-field (B) from the Lauderhill muck were twice as high as the P value from the sugarcane-fallow field (A). According to the kriged-contour maps, the Okeelanta muck showed the highest soil variability, while the Torry muck showed the lowest.

Once the spatial scale of variation and problem areas in the field have been identified, sampling can be optimized. These results showed that there is a large variability between fields in the same location and among different soil series. Soil pH_w was the most uniform soil

property in the middle of the fields requiring only four to six samples to produce a value with 5% error at the 90% confidence level. On the contrary, Mg, K, and P were quite variable, requiring larger numbers of samples to obtain a dependable value. A practical number of samples for Mg and P is 15 to 20 to produce values within 20% of the population mean at the 95% confidence level. A practical number of samples for K is also 15 to 20 to produce K values within 20% of the population mean at the 90% confidence level. A similar number of samples is also applicable for micronutrients. The acceptance of large relative errors to minimize sampling efforts indicates that accurate soil sampling in Histosols of the EAA is not an easy task.

Use of geostatistical techniques in the Histosols of the EAA, contributed to a better understanding of the behavior of the spatial variability of selected chemical properties. This information is of extreme importance to farm managers to assist them in cultural practices such as soil sampling and fertilizer recommendations.

CHAPTER 5
REGIONAL VARIATION OF SELECTED SOIL CHEMICAL PROPERTIES IN THE EVERGLADES AGRICULTURAL AREA

Introduction

Soil variability is the product of the interaction of soil-forming factors operating with varying intensity over a continuum of spatial and temporal scales. Spatial variability of soil properties occurs over different levels of generalization, ranging from regional differences, such as those described by mapping units (Yost et al., 1982b; Trangmar et al., 1984) to small changes in physical and chemical properties that occur within the rhizosphere of single plants (Beckett and Webster, 1971).

Soil classification and its field application through soil survey operations have been one of the most commonly used methods to describe soil variability on a regional scale (Beckett and Webster, 1971; Wilding and Drees, 1978). Soil classification and soil survey tend to group soils that are reasonably homogeneous and separate those that are different into other categories. This approach constitutes the basis for establishing relationships among individual soils, predicting soil behavior, and identifying potential land uses (Buol et al., 1989). However, human management

can introduce additional sources of soil variability depending on the kind and intensity of land use of a particular area within a mapping unit. Soil properties, such as soluble P and exchangeable cations, are more affected by soil management and commonly more variable than morphological and physical properties (Beckett and Webster, 1971; Adams and Wilde, 1976a, 1976b).

One technique that can be used to display and analyze spatial variation is geostatistics. Geostatistical methods have been used to describe and quantify the structure of spatial dependence of soil properties. This property enables geostatistics to evaluate and map soil variability of selected properties within experimental plots (Webster and McBratney, 1987), land management units (Burgess and Webster, 1980a, 1980b; Vieira et al., 1981), and over large land areas (Yost et al., 1982a, 1982b; Trangmar et al., 1984; Xu and Webster, 1984).

Approximately 90% of the soils in the Everglades Agricultural Area (EAA) are Histosols (Anderson, 1990a). These soils are classified according to the thickness or the depth of the organic horizon to the bedrock. Underlying the majority of these organic soils is the Pleistocene age Ft. Thompson formation, which consist of alternating beds of limestone, shell, sand, and marl.

The EAA is one of the most productive agricultural areas in the United States. The main crops grown in the

area are sugarcane (Saccharum spp.) and winter vegetables, with sod, rice (Oriza sativa L.), and some cattle production accounting for the remaining agricultural production. Cropping generally incorporates additional sources of soil variability. Cropping practices in the EAA may change the soil-nutrient status through row cultivation, fertilization, crop-nutrient removal and water-table management.

The objectives of this study were to (i) summarize regional variation of selected chemical properties from the surface 15 cm of soil of the EAA and surrounding areas; (ii) create a data base containing the geographical location of the EAA and surrounding areas in the Township, Range, Section (TRS system), and State Plane coordinate systems, and (iii) map the spatial distribution and associated variance errors of selected chemical properties from the EAA using block kriging, to have a better understanding of how soil variability is related to soil geography and soil management.

Materials and Methods

Data Collection and Laboratory Analysis

Information used in this study comes from surface soil samples (0 to 15-cm depth) submitted by growers to the Everglades Soil Testing Laboratory, Belle Glade, during 1987. Each sample was identified as to its geographic location using the TRS system.

Soil samples were assumed to be composites of 10 to 20 cores taken across 16 to 24 ha fields. These samples were thoroughly mixed and a subsample taken for laboratory analyses. Soils were air-dried at 38 °C for 72 h and passed through a 2-mm sieve before chemical analyses.

Soil pH was determined in a 1:2 soil:water suspension (pH_w). Soil samples were analyzed by the Everglades Soil Testing Laboratory, Belle Glade, for water and 0.5 M acetic acid extractable P (P_w and P_a, respectively; 4:50, soil:extracting solution by volume), and K_a, Ca_a, and Mg_a (10:25 soil:extracting solution by volume) (Thomas, 1965a; Sanchez, 1990).

Soil samples are assumed to be randomly collected within a section (one section is equivalent to 1 mi^2, 259 ha), at intervals ranging from 500 m to 1 km. An average of 10 fields were sampled and analyzed within each particular section. However, for the purpose of mapping, all data collected from each section (10 values) were averaged and used as the overall value coming from that section. A total of 302 sections throughout the EAA and surrounding areas were sampled for this study (Fig 5-1).

Statistical and Geostatistical Analyses

Statistical and geostatistical procedures used in this study are described in Chapters 3 and 4.

Mapping

The production of contour maps of soil properties is one of the most common and important attributes of block kriging (Burgess and Webster, 1980b; Trangmar et al., 1985). To take advantage of the mapping ability of block kriging, a data base of the geographical location of the EAA and surrounding areas was created. The data base was created by inputing the geographical location of the EAA using the TRS system. The TRS system takes advantage of the similar labeling procedure used by growers submitting soil samples to the Everglades Soil Testing Laboratory. To use the TRS system for mapping, equivalent State Plane values (ft) were incorporated into the data set. State Plane values were generated by digitizing several locations across the EAA from a Geological Survey Map of the area. The digitized locations corresponded to the center of specific TRS coordinates, which were used as the initial points to transform the entire data set to State Plane values. The created data base composed of TRS and corresponding State Plane values was used as a look-up table to locate soil data coming from the EREC Soil Testing Laboratory using the TRS system. A SAS merging procedure (SAS, 1982a) was used to create a new data file containing the soil data and State Plane coordinates which was used in the block kriging procedure (Yost et al., 1989).

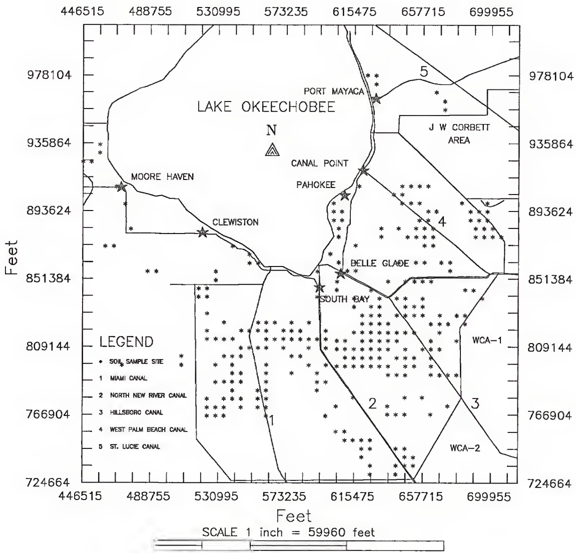

Fig. 5-1. Main geographic features and sample location of the study area, EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

Block kriging was used to estimate values at unsampled locations, to create a fine grid of points that is necessary for mapping procedures. Values for pH_w, P_w, K_a, P_a, Mg_a, and P_w/P_a ratio were kriged at 500 locations throughout the EAA and surrounding areas. Each kriged value represents the center of a 4-section block (10.36 km^2) . Contour maps of kriged values and estimation variance were generated using the program SURFER Version 4 (Golden Software, Inc., 1990).

Results and Discussion

Spatial Analysis

The mean, range, variance, and % CV of selected chemical properties from the 1987 mapping soil data set are shown in Table 5-1. Sample probability distributions of the majority of the soil chemical properties were lognormal as determined by the Kolmogorov-Smirnoff D statistic. Therefore, geostatistical analyses were performed on log-transformed data. Important parameters for direction-dependent and direction-independent semi-variograms for selected chemical properties are given in Tables 5-2 and 5-3, respectively.

Soil pH_w, P_a, and K_a were the only soil chemical properties showing anisotropy (Figs. 5-2, 5-3, and 5-4). These results indicate that the spatial variability of these soil chemical properties changed with direction across the EAA. Semi-variograms in the N-S direction for pH_w, P_a, and

Table 5-1. Summary statistics of selected soil chemical properties from the surface 15 cm of samples collected from the EAA and surrounding areas, 1987.

Soil property	Mean	Range	Variance	CV (%)	Number of samples
	--------- Soil Testing Laboratory, EREC ---------				
pH-H_2O	6.6	4.8 - 8.3	0.380	9.3	302
P_w, mg L^{-1}	7.4	1.0 - 46	62.2	107	302
P_a, mg L^{-1}	29	7.0 - 134	505	77	165
K, mg L^{-1}	73	8.0 - 389	3482	81	302
Ca, g L^{-1}	2.6	0.25 - 3.7	0.885	36	129
Mg, g L^{-1}	0.32	0.015 - 0.74	0.0427	65	129
P_w/P_a	0.20	0.020 - 0.76	0.0209	73	165

Table 5-2. Spatial dependence of selected soil chemical properties from the surface 15 cm of samples from the EAA and surrounding areas, 1987.

Direction†	Nugget variance	Sill	General variance	Slope	Range (ft)	% of sill
			pH-H_2O			
Isotropic	0.1935	0.3797	0.3804	-	110322	51
N - S	0.2028	-	0.3804	$2.2x10^{-6}$	-	Unbounded
E - W	0.1833	0.3529	0.3804	-	89067	52
			Log P_a‡			
Isotropic	0.2177	-	0.3817	$1.7x10^{-6}$	-	Unbounded
N - S	0.1761	-	0.3817	$2.8x10^{-6}$	-	Unbounded
E - W	0.2528	0.3340	0.3817	-	116778	76
			Log K			
Isotropic	0.4605	0.6968	0.6339	-	122801	66
N - S	0.4861	-	0.6339	$1.9x10^{-6}$	-	Unbounded
E - W	0.4361	0.6976	0.6339	-	112367	63

† Measurements were calculated from 302 (pH and K), and 165 (P_a) observations.
‡ 0.5 M acetic acid extractable P and K.

Table 5-3. Spatial dependence of selected soil chemical properties from the surface 15 cm of samples from the EAA and surrounding areas based on isotropic semi-variograms, 1987.

Soil property†	Nugget variance	Sill	General variance	Slope	Range (ft)	% of sill
Log P_w‡	0.5683	0.8714	0.7780	-	86709	62
Log Ca	0.0849	-	0.3255	2.4×10^{-6}	-	Unbounded
Log Mg	0.1736	-	0.8685	6.0×10^{-6}	-	Unbounded
Log P_w/P_a	0.1301	0.5954	0.5060	-	89806	22

† Measurements were calculated from 302 (P_w), 129 (Ca and Mg), and 165 (P_w/P_a) observations.
‡ Water extractable P (P_w).

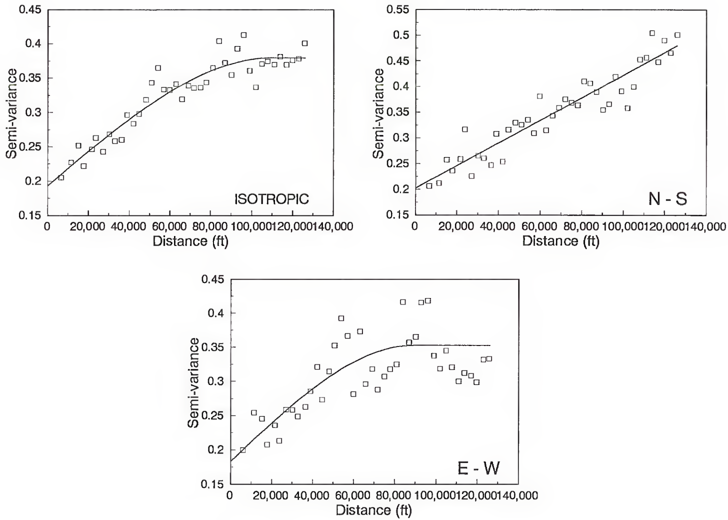

Fig. 5-2. Isotropic and direction-dependent semi-variograms of soil pH_w from the EAA and surrounding areas, 1987. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

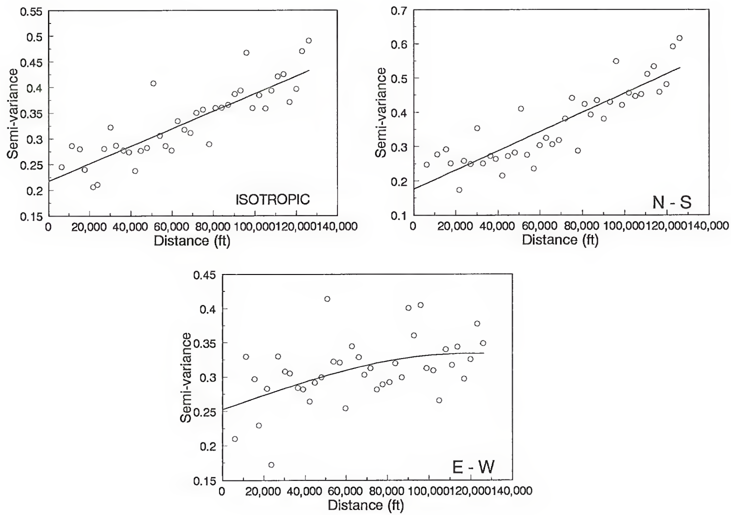

Fig. 5-3. Isotropic and direction-dependent semi-variograms of soil P_a from the EAA and surrounding areas, 1987. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

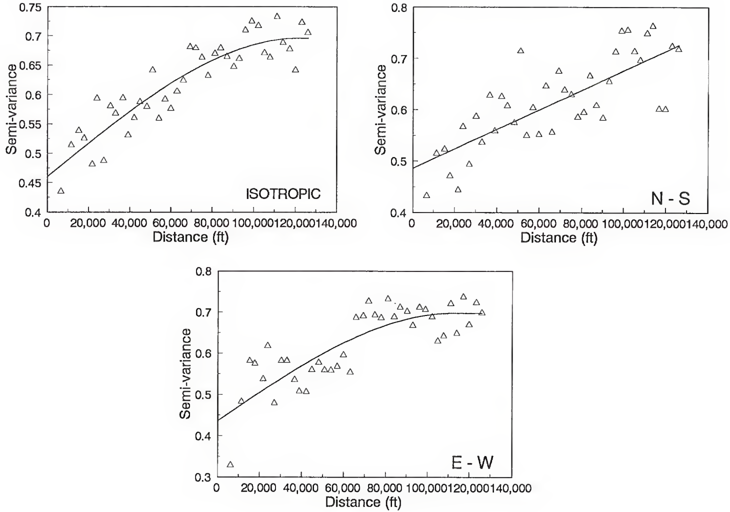

Fig. 5-4. Isotropic and direction-dependent semi-variograms of soil K_a from the EAA and surrounding areas, 1987. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

K_a were better fitted by a linear model. These semi-variograms increased unbounded and had no sill. Potassium (N-S semi-variogram) showed the largest intercept (nugget variance) plus a substantial scatter about the fitted line. These results suggested that more sampling is needed in this direction to establish the true form of the semi-variogram. Soil pH_w and P_a showed a better fit and smaller intercepts than K_a. Linear semi-variograms indicated constant changes of those soil properties in that particular direction. Soil pH_w, P_a, and K_a showed constant change in the N-S direction across the EAA.

In contrast, semi-variograms in the E-W direction were well structured with distinctive nugget variances (intercept), ranges, and sills (Figs. 5-2, 5-3, and 5-4). Soil pH_w showed the shortest range (89,067 ft) as well as the lowest nugget variance (52% of the sill) of the three soil properties in the E-W direction. Therefore, on a regional scale, soil pH_w values separated by a distance less than 89,067 ft (16.87 mi) are spatially dependent. Acetic acid-extractable P showed a substantial scatter about the fitted curve as well as the largest nugget variance (76% of the sill), implying that additional sampling is needed to calculate a more precise semi-variogram. The large nugget variance means that there is 76% of the unexplained random variance due to measurement errors or spatial variability at distances shorter than 1 mile (1.61 km).

Parameters for isotropic (direction-independent) semi-variograms are given in Table 5-3. Water extractable-P and the ratio P_w/P_a produced well structured semi-variograms, while Ca and Mg were better fitted by a straight line (unbounded) (Fig. 5-5). Water extractable-P showed a large nugget variance that accounted for 62% of the sill. This means 62% of the error was caused either by measurement errors or microvariability of P_w which was not detected at the sampling distance used. Therefore, more sampling is needed at distances shorter than 1 mile to account for the unexplained random variance. Soil Ca_a and Mg_a semi-variograms showed a constant change across the EAA (unbounded).

Regional Variation

Kriging has the advantage of providing estimates for coordinate position within the measured domain without bias and with minimum variance. Using the structural information derived from the fitted semi-variograms (Tables 5-2 and 5-3), values of selected chemical properties were block-kriged at 500 State Plane coordinates (Yost et al., 1989). Kriged values and their respective estimation variances were used to produce contour maps of pH_w, P_w, P_a, P_w/P_a, K_a, and Mg_a (Figs. 5-6 through 5-15 and Appendix C).

Block-kriged pH_w and estimation variance contour maps are shown in Figs. 5-6 and 5-7, respectively. Soil pH_w

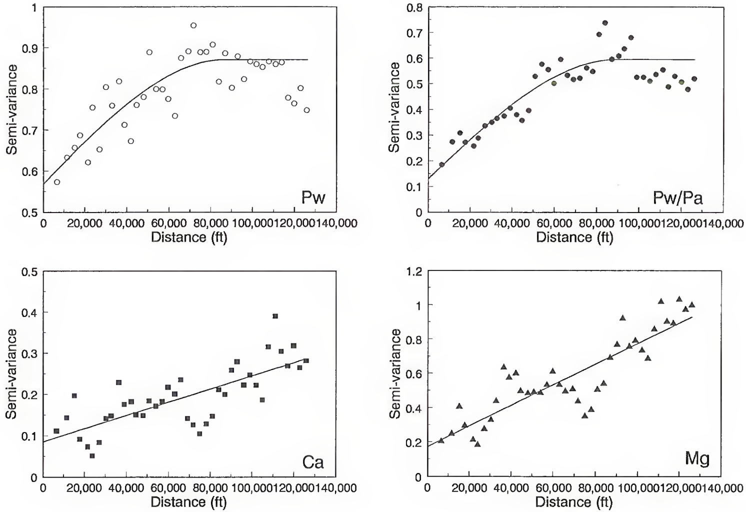

Fig. 5-5. Isotropic semi-variograms of soil P_w, P_w/P_a, Ca_a, and Mg_a across the EAA and surrounding areas, 1987. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

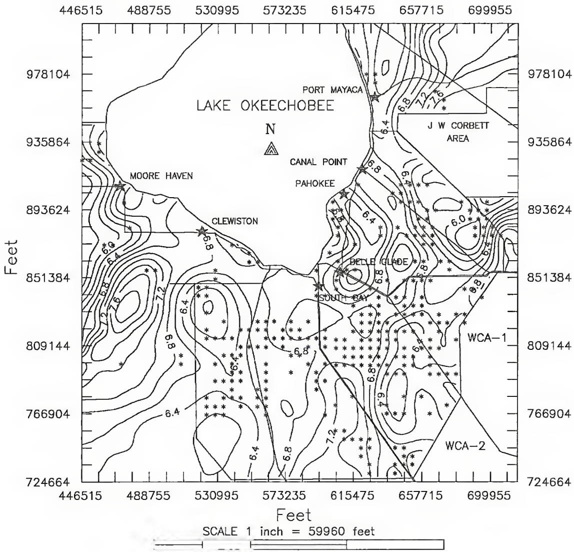

Fig. 5-6. Block-kriged contour map of soil pH_w from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

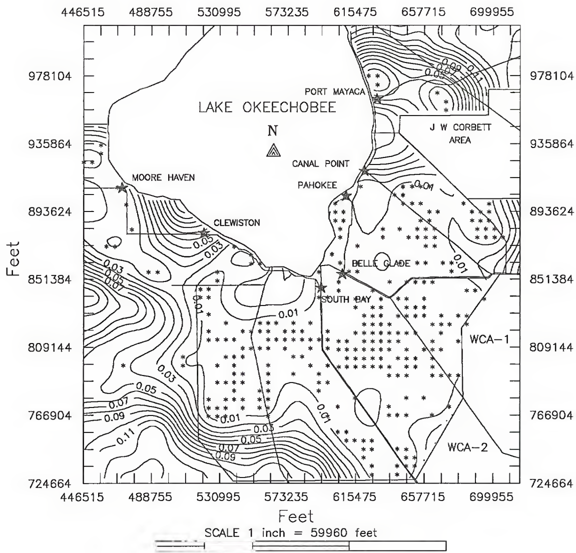

Fig. 5-7. Block-kriged contour map of soil pH_w estimation variance from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

values throughout the EAA and surrounding areas varied from 4.8 to 8.3 (Table 5-1). On the average, soil pH_w in the EAA ranges from about 6.2 to 6.6, with values increasing toward the borders of the EAA (Fig. 5-6). However, it is likely that soil pH_w in the EAA will increase in the future as soils continue to subside. Most of the soils in the EAA are underlain by the Fort Thompson formation consisting of alternating beds of limestone, shell, sand, and marl. In a recent survey, it was shown that the percentage of deeper soils in the EAA has dropped dramatically during the past 10 yr. Currently, 67% of the organic soils of the EAA belong to the series Pahokee (27.4%) and Lauderhill (39.6%) (Soil Conservation Service, 1988; Anderson, 1990a; Smith, 1990). Figure 5-6 also shows some low pH_w areas located around the Twenty Mile Bend area (south of J.W. Corbett Area). This area is characterized for having acidic organic soils of the Okeelanta series, with pH_w values as low as 4.8. Soil pH_w values increased toward the sandy soils located on and beyond the EAA boundaries. Soil pH_w in the sandy soils of the NE section of the map (around the St. Lucie Canal) show pH_w values as high as 7.8. Similar high pH_w values are observed in sandy soils south of Moore Haven. Additional data will be needed to increase the reliability of these estimates.

The kriging technique also provides an indication of the reliability of the estimates in the form of estimation

variances. Estimation variances for kriged values of soil pH_w varied from 0.01 in those areas where sampling was more intensive to 0.14 where samples were sparse (Fig. 5-7). The low variances around the areas of intensive sampling indicate precision of the pH_w estimates done by kriging. In contrast, large variances indicate those areas where additional sampling are needed to improve the precision of estimations. In Fig. 5-7, the largest estimation variances come from areas bordering the EAA in the NE and SW areas of the map where samples were sparse or not taken at all. Variances were also large at the Holey Land Wildlife Management Area located north of the Palm Beach-Broward county line (the area at the bottom of the map). Contour lines of soil pH_w were not estimated in the Loxahatchee National Wildlife Refuge (WCA-1), Conservation Area No. 2 (WCA-2), and the J.W. Corbett Wildlife Management Area.

Soil P_w concentrations ranged from 1.0 to 46 mg L^{-1} (Table 5-1). Results from Fig. 5-8 show that the highest concentrations of P_w are located in some of the most intensively cultivated areas (SE corner of the EAA). Phosphorus concentrations decreased toward the boundaries of the EAA, especially in the sandy areas of Martin county (NE corner of the map), and Hendry county (SW section of the map). The reliability map of kriged P_w values (Fig. 5-9) followed the same pattern as that shown by pH_w. Estimation variances ranged from as low as two in the more intensively

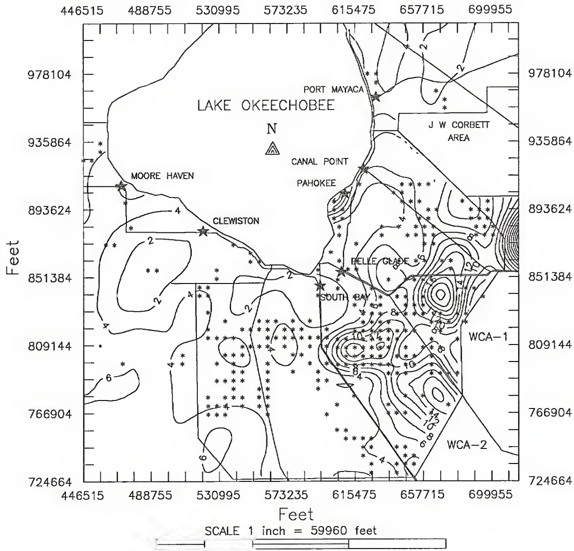

Fig. 5-8. Block-kriged contour map of soil P_w (mg L^{-1}) from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

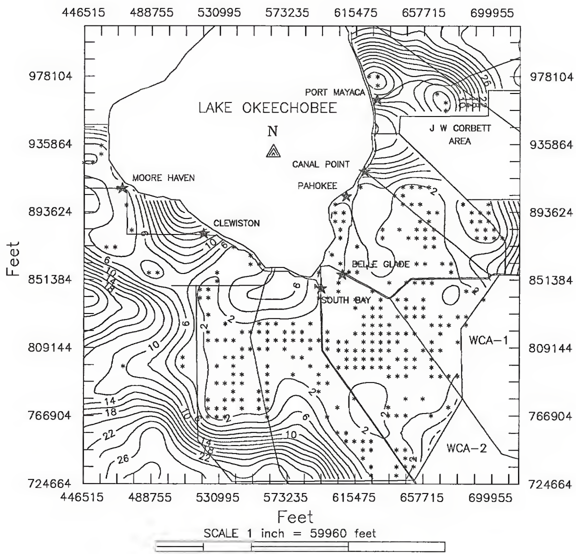

Fig. 5-9. Block-kriged contour map of soil P_w estimation variance from the EAA and surrounding areas. Contour lines are in units of $(mg\ L^{-1})^2$. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

sampled areas, to as high as 30 in the unsampled areas. The P_w estimation variances are not excessively large considering the range in concentrations (1.0 to 46 mg L^{-1}) and diversity of soils sampled in the area. The estimation variances give standard deviations ranging from 1.4 mg P L^{-1} in most of the organic soils of the EAA to 5.3 mg P L^{-1} in the sandy soils of Martin and Hendry counties bordering the EAA.

Soil P_a ranged from 7 mg L^{-1} in the sandy soils to 134 mg L^{-1} in the organic soils (Table 5-1). The highest concentrations of P_a are located in the area N and NE of Belle Glade (Fig. 5-10). This area around Lake Okeechobee is where most of the Torry mucks are located. Torry muck is one of the most productive soils in the EAA. Total P in these soils (2310 mg P kg^{-1}) is three to six times higher than total P from other major soils series in the EAA (Appendix A). High P_a are also shown in upper right corner of the map (north of the J.W. Corbett Area). However, additional data are necessary to increase the reliability of these estimates. Soil P_a estimation variance map gave standard ranging from 3.2 mg L^{-1} in the areas of sampling density to 11.4 mg L^{-1} at unsampled locations (Fig. 5-11).

Results from Fig. 5-12 show that most of the EAA and surrounding areas have low P_w/P_a ratios, with the exception of the areas south of the Corbett area and east of WCA-2. According to a recent soil survey, most of the soil of those

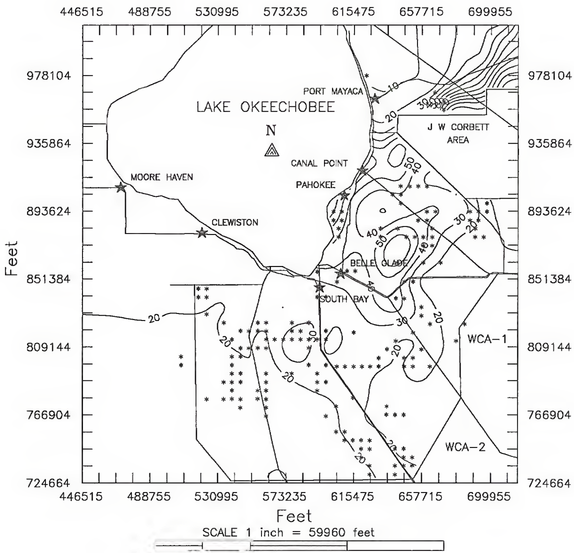

Fig. 5-10. Block-kriged contour map of soil P_a (mg L^{-1}) from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

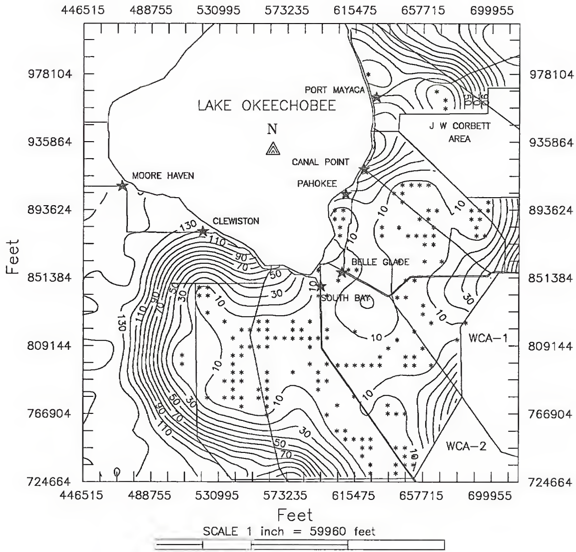

Fig. 5-11. Block-kriged contour map of soil P_a estimation variance from the EAA and surrounding areas. Contour lines are in units of $(mg\ L^{-1})^2$. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

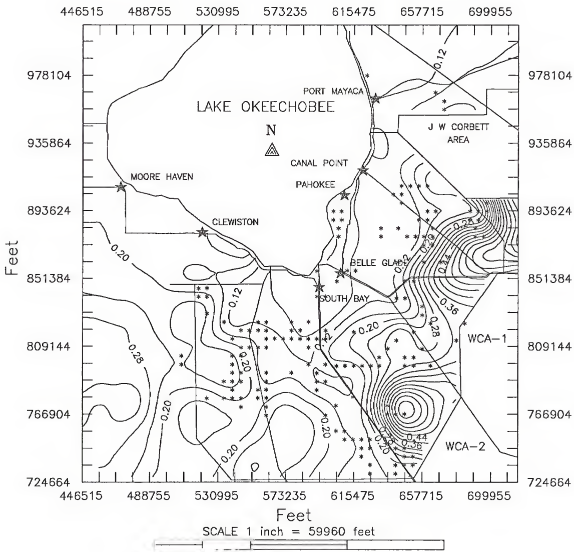

Fig. 5-12. Block-kriged contour map of soil P_w/P_a from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

two areas belong to the series Okeelanta and Pahokee (Soil Conservation Service, 1988). Similar high ratios were observed in Pahokee and okeelanta fields discussed in Chapter 4 (Fig. 4-5). High P_w/P_a ratio means that a high percentage of P supplied either through fertilization or mineralization, is available and can be removed easily. In contrast, low ratios mean that P is tightly held and its removal is more difficult. Thus, areas with high P_w/P_a ratios have a greater P loss potential than those with low ratios. The reliability P_w/P_a map showed the same pattern as that shown by P_w and P_a (Fig. 5-13).

Soil K_a ranged from 8.0 mg L^{-1} in the sandy soils to 389 mg L^{-1} in the organic soils of the EAA (Table 5-1). The highest concentrations of K_a are also located in the more intensive cultivated areas of the EAA (Fig. 5-14). Total K content of most organic soils is about one-tenth of that found in mineral soils (< 550 kg ha^{-1} on a volume basis) (Lucas, 1982; Anderson, 1990a). Potassium released from fertilizers or mineralized from organic matter is weakly held on the exchange sites. Because of the weak bonding of K to the exchange sites, leaching loses in organic soils are larger than from most mineral soils. For this reason, large quantities of K fertilizer are needed for crop production in the EAA. Soil K_a estimation variances give standard deviations ranging from 10 mg L^{-1} in the areas of high sampling density to 37 mg L^{-1} at unsampled locations

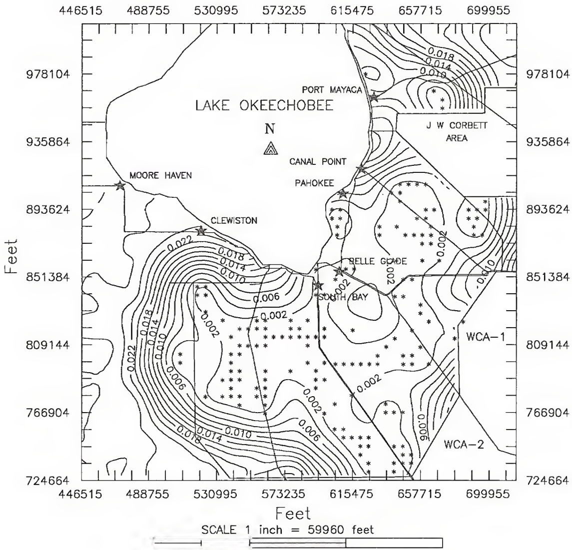

Fig. 5-13. Block-kriged contour map of soil P_w/P_a estimation variance from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

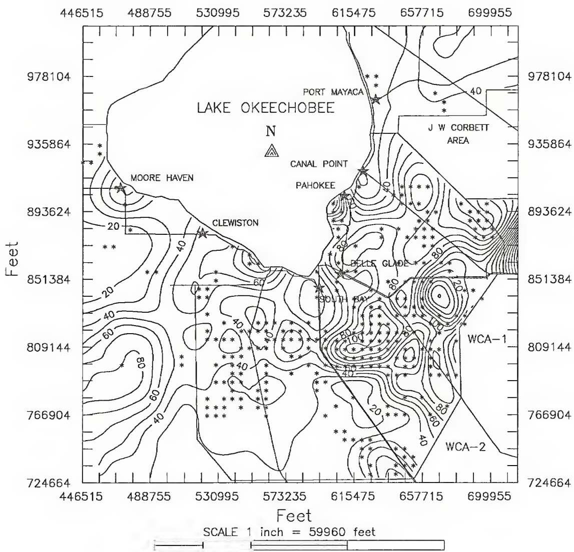

Fig. 5-14. Block-kriged contour map of soil K_a (mg L^{-1}) from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

(Fig. 5-15). Additional sampling taken from these regions would rapidly reduce the estimation variances improving the quality of this map.

Conclusions

Block-kriged contour maps show patterns of regional variation of agronomically important soil chemical properties in the EAA. These maps show regional variations of soil chemical properties due to soil type as well as soil management. Contour maps show that the average soil pH_w in most of the organic soils of the EAA are between 6.4 and 6.6, with the exception of the low pH_w area of Twenty Mile Bend. High pH_w values in the EAA may be related to the proximity of calcium carbonate parent material in the soil profile. Recent studies have shown that 40% of the area is less than 1 m deep, with another 27% less than 1.3 m deep.

Phosphorus and K variability was shown in several areas of the EAA. The highest P_w and K_a concentrations were located in some of the most intensive cropped areas of the EAA. Therefore, soil P_w and K_a variability in the EAA may be highly related to the intensity of crop production and soil management. In contrast, soil P_a, although influenced by soil management, soil series appears to have a higher influence on its regional variability. The highest P_a concentrations were located in the area where most of the Torry muck of the EAA are concentrated. Generally, total P

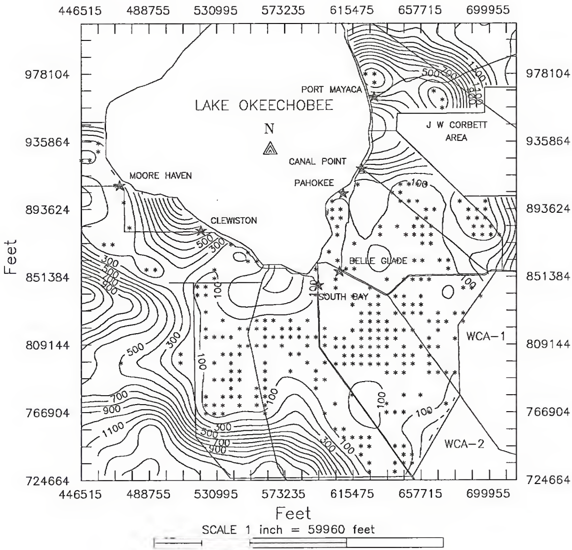

Fig. 5-15. Block-kriged contour map of soil K_a estimation variance from the EAA and surrounding areas. Contour lines are in units of $(mg\ L^{-1})^2$. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

of Torry mucks is three to six times higher than total P of the other soils series of the EAA. Results from the soil P_w/P_a map showed low ratios in most of the soils of the EAA, with the exception of a couple of high ratio areas. Generally, higher P_w/P_a ratio areas have a greater P loss potential than low ratio areas.

Kriging is one of the best techniques of making optimal unbiased estimates of regionalized variables at unsampled locations. Kriging was shown to be a valuable technique to evaluate spatial soil variability on a regional scale.

An additional advantage of kriging is that the estimate variance can be calculated, providing a measure of interpolation reliability. The estimation variance map indicated those areas where additional sampling is needed to improve confidence levels. Block-kriged estimate variance maps gives valuable information to improve the design of future sampling strategies.

CHAPTER 6
NITROGEN AND PHOSPHORUS MINERALIZATION IN ORGANIC SOILS OF THE EVERGLADES AGRICULTURAL AREA

Introduction

Organic soils (Histosols) are formed from partially decomposed plant and animal remains that have accumulated under flooded (reduced) conditions. When soils are drained, the protective effect of high moisture is lost, which results in rapid breakdown of organic matter causing subsidence (Stephens, 1956). Among the products of organic matter oxidation are various forms of nitrogen (N) and P such as NH_4^+, NO_3^-, and soluble organic nitrogen (SON), ortho-P (PO_4^{-3}), and soluble organic phosphorus (SOP). Several studies have indicated that drained organic soils are sources of excess nitrates which may contaminate surface and ground waters (Hortenstine and Forbes, 1972; Duxbury and Peverly, 1978). Since nitrogenous fertilizers are rarely applied to organic soils, the major source of N found in the soil and drainage waters must result from mineralization of organic matter.

Many processes of N transformation occur simultaneously in the soil. Nitrogen that is mineralized due to microbial oxidation of the organic matter may be returned to the

organic form through immobilization or lost to the atmosphere through denitrification. Neller (1944) reported NO_3^--N concentrations as high as 422 mg kg^{-1} (222 kg N ha^{-1}) in uncropped Everglades peats. Similar high concentrations have been reported from several mineralization studies in organic soils under aerobic conditions (Avnimelech, 1971; Isirimah and Keeney, 1973; Terry, 1980; Reddy, 1982). Terry (1980) reported that approximately 668 kg N ha^{-1} were mineralized for each centimeter of Pahokee muck lost due to microbial oxidation. Reddy (1982) reported N mineralization rates from 410 to 938 kg ha^{-1} yr^{-1} for uncropped organic soils. However, when these soils are under flooded and reduced conditions, NO_3^--N concentrations decline (Avnimelech, 1971; Isirimah and Keeney, 1973; Reddy, 1982). Under anaerobic conditions, NH_4^+-N accumulates due to the dissimilatory reduction of NO_3^--N to NH_4^+-N during anaerobic respiration and the suppression of nitrification (Isirimah and Keeney, 1973; Guthrie and Duxbury, 1978; Buresh and Patrick, 1978; Buresh and Patrick, 1981; Reddy, 1982). Guthrie and Duxbury (1978) found that under flooded conditions, the amount of NH_4^+-N accumulated was four times higher than that measured in drained soils.

Most virgin Histosols contain from 0.01 to over 0.3% P, of which 30 to 85% of the total P is in organic form and must be mineralized before plant utilization (Waksman, 1936; Lucas, 1982). Organic P accumulates in soils following

microbial transformations of inorganic and plant-residue P into stable organic-P forms. A portion of the total organic P is also hydrolyzed to orthophosphate. Hortenstine and Forbes (1972) reported P concentrations as high as 30 mg kg^{-1} (15.8 kg P ha^{-1}) in solution from unfertilized organic soils from Florida. Reddy (1983) reported soil P mineralization rates from 38 to 185 kg ha^{-1} yr^{-1} for Central Florida organic soils and 16 to 23 kg P ha^{-1} yr^{-1} for South Florida organic soils.

Flooded organic soils release higher levels of soluble P compared to drained organic soils. Reddy (1983) reported P-release values four to six times higher from flooded organic soils than from drained organic soils. Racz (1979) found that total and all extractable forms of P were usually greater on samples incubated under flooded conditions than on samples incubated at field capacity. The higher P release from organic soils under flooded conditions is probably caused by the solubilization of organic matter during anaerobic decomposition (Mahapatra and Patrick, 1969; Reddy, 1987). Flooding may also increase the release of soluble inorganic P by increasing the solubilization of Fe, Al, and Ca-phosphates under reduced conditions (Reddy, 1987). The objective of this study was to quantify the effect of intermittent flooding and drained conditions on N and P release into drainage waters from Histosols sampled from the Everglades Agricultural Area (EAA).

Materials and Methods

Collection of Soils and Preparation of Columns

Composite surface samples (0 to 15-cm depth) of four different soil series were used in this study (Table 6-1). The soils were collected in the spring of 1988 from five locations across the EAA. Surface samples of a Pahokee muck (euic, hyperthermic Lithic Medisaprist) were collected from an uncultivated location at the Everglades Research and Education Center, Belle Glade, and from a cultivated field that had been planted to sugarcane (*Saccharum* spp.) during the past 5 years. Surface samples of Lauderhill muck (euic, hyperthermic Lithic Medisaprist) were collected from a field that had been in sod production [St. Augustine grass, *Stenotaphrum secundatum* (Walt.) Kuntze] for 2 years. Surface samples of Okeelanta muck (euic, hyperthermic Terric Medisaprist) were collected from a first year sugarcane field, previously planted to sweetcorn (*Zea mays* L.). Surface samples of a Torry muck (euic, hyperthermic Typic Medisaprist) were collected near the city of Pahokee from a field that had been under sweetcorn production for the last 2 years. Selected physical and chemical characteristics of these soils are listed in Tables 6-2 and 6-3.

Polyvinyl chloride (PVC) pipes (5.0-cm i.d.) were used to construct 40 columns, each 20 cm long, for this study. The bottom part of each column was sealed with a PVC cup

Table 6-1. Description of five organic soils from the EAA used in the incubation study.

Soil series	Classification	Crop history	Location Rng	Twn	Sec
Pahokee (U)	euic, hyperthermic Lithic Medisaprist	Uncultivated	37	44	3
Lauderhill	euic, hyperthermic Lithic Medisaprist	Sod	37	45	19
Pahokee	euic, hyperthermic Lithic Medisaprist	Sugarcane	38	45	6
Okeelanta	euic, hyperthermic Terric Medisaprist	Sugarcane	39	43	2
Torry	euic, hyperthermic Typic Medisaprist	Sweetcorn	37	42	29

Table 6-2. Selected physical characteristics of five organic soils.

Soil series	Bulk density	Ash content	Water content at 100-cm suction
	$g\ cm^{-3}$	%	$cm^3\ cm^{-3}$
Pahokee (U)	0.35	15.2	0.44
Lauderhill	0.35	17.0	0.55
Pahokee	0.35	14.0	0.59
Okeelanta	0.37	20.0	0.67
Torry	0.65	58.4	0.47

Table 6-3. Selected chemical characteristics of five organic soils.

				Phosphorus		
Soil series	pH	Total C	Total N	Water soluble	Mehlich I-extractable	Total
		%	$g\ kg^{-1}$	---- $\mu g\ P\ cm^{-3}$ of soil ----		
Pahokee (U)	5.09	42.5	32.7	0.57	2.72	279.1
Lauderhill	6.56	43.3	29.9	0.90	23.05	280.2
Pahokee	5.26	44.2	33.2	10.68	17.93	222.1
Okeelanta	4.98	37.9	28.0	10.86	18.44	155.9
Torry	5.15	16.5	16.5	8.31	132.85	1736.5

provided with an outlet to allow the application of suction during each leaching period. A layer of glass wool was placed at the bottom of each column to avoid soil loss during leaching. A known amount of soil was manually packed in each column to a depth of 15 cm. The amount of soil packed into each column was calculated on an oven-dry basis (70 °C for 24 h), based on moisture content and bulk density (Table 6-2).

Incubation and Leaching Procedures

The incubation study was established using five soils and two moisture (drained and intermittent flooding) combination treatments, and four replications arranged in a randomized complete-block design. Soil columns were incubated under laboratory conditions. The maximum temperature during the study was 29 °C and the minimum 21 °C. The columns were leached with 250 mL of 0.01 M $CaCl_2$ followed by 200 mL of distilled water to remove initial NO_3^-, NH_4^+, SON and P from the soil. Soil columns were allowed to drain naturally followed by the application of 100-cm H_2O suction. Leachates obtained at the beginning of the study were analyzed for NO_3^-, NH_4^+, SON, soluble reactive phosphorus (SRP), and total P (TP) (Table 6-4). These results were not used in the estimation of N and P mineralization potential of these soils.

Table 6-4. Various forms of N and P in the soil columns at the beginning of the study.

Soil series	NO_3^--N	NH_4^+-N	SON	SRP	TP
	--------------		$\mu g\ cm^{-3}$ of soil†		--------------
Pahokee (U)	111.97	0.55	7.90	2.10	2.73
Lauderhill	79.42	0.68	8.25	1.53	1.69
Pahokee	149.60	0.64	8.90	4.98	6.35
Okeelanta	116.01	0.65	8.29	6.83	8.45
Torry	153.60	0.53	7.82	5.03	6.36

† Average of four replications.

Soil columns were leached each 25 d with 250 mL of 0.01 M $CaCl_2$ followed by 200 mL of distilled water for 325 d. Drained columns were incubated with a minus-NP (0.002 M $CaSO_4 \cdot 2H_2O$, 0.002 M $MgSO_4$, and 0.0025 M K_2SO_4) solution (Stanford and Smith, 1972) after applying 100 cm-H_2O suction to maintain soil moisture at optimum level for organic matter decomposition (Terry, 1980; Reddy, 1982). Intermittent-flooded columns were maintained with the minus-NP solution to a depth of 3 cm for the same 25-d periods, followed by leaching as described for drained columns. After each leaching, the volumes of the leachates was measured and analyzed for NO_3^-, NH_4^+, SON, total N, and TP. A portion of the leachates was filtered through 0.45-μm membrane filter and analyzed for SRP. At the end of the study, soil columns were taken apart and a representative soil sample from each column was taken and analyzed for the same elements.

Laboratory Analysis

Soil samples at the beginning and at the end of the study were analyzed at the moisture condition they had when collected and when the study was terminated. However, all calculations were based on oven-dry weights. Bulk density was measured by the core method (Blake and Hartge, 1986). Ash content was determined by igniting 5 g of oven-dried soil at 500 °C for 5 h (Anderson and Beverly, 1985). Soil

moisture tension curves were determined by pressure plates. Soil pH was determined in 1:2 soil water suspension by glass electrode. Total carbon was estimated by the wet oxidation method (Walkley, 1947; Nelson and Sommers, 1982) and total soil N by the micro-Kjeldahl procedure (Bremner and Mulvaney, 1982), at the beginning and at the end of the study.

Ammoniacal-N and NO_3^--N in the soil at the end of the study were extracted with 2 M KCl solution (1:10, soil:solution by weight) (Keeney and Nelson, 1982) and analyzed colorimetrically in an Alpkem Rapid Flow Autoanalyzer. Analytical methods used for NH_4^+-N and NO_3^--N were the automated phenate method and the automated cadmium-reduction method (APHA, 1985). Soil samples were also extracted with a 1:10, soil:water ratio after 1 h shaking. The filtrate was analyzed for SON and water-soluble P. Mehlich I-extractable P was measured by extracting 2.5 g of soil (oven-dry basis) with 25 mL of the extracting solution for 5 min. Total P in the soil was measured by igniting 1 g of soil at 550 °C for 3 h (Olsen and Sommers, 1982). The residue was dissolved in 6 M HCl and total P analyzed colorimetrically (Murphy and Riley, 1962).

Leachates collected every 25 d were analyzed for NH_4^+-N, NO_3^--N, total Kjeldahl N (TKN), SON, SRP, and TP. Leachate samples for NH_4^+-N and NO_3^--N were acidified to pH 2 and immediately frozen until analyzed following the

procedures described by APHA (1985). Total P and TKN samples were stored at 4 °C until analyzed. Total P and TKN were measured by block digestion of 10 mL of leachate in the presence of H_2SO_4, and $HgSO_4$ for 2.5 h at 380 °C. Total P and TKN were colorimetrically analyzed on a Technicon Autoanalyzer (AAII), by the automated phenate method and the automated ascorbic acid reduction method, respectively. Leachate samples for SRP analyses were filtered through a 0.45-μm membrane filter, acidified to pH 2 and stored at 4 °C until analyzed. Soluble reactive P was colorimetrically analyzed on an AAII by the automated ascorbic-acid method (APHA, 1985).

Statistical Analyses

Data were analyzed as a completely randomized factorial design. Analyses of variance and mean comparison were done by SAS statements given by Freund and Littell (1981).

Results and Discussion

Nitrogen

Ammonium-nitrogen

Ammoniacal-N released from drained organic soils ranged from 0.34 to 0.58 $\mu g\ cm^{-3}$ of soil per leaching period during the entire study (Fig. 6-1). Previous incubation studies under well-drained conditions have shown that NH_4^+-N

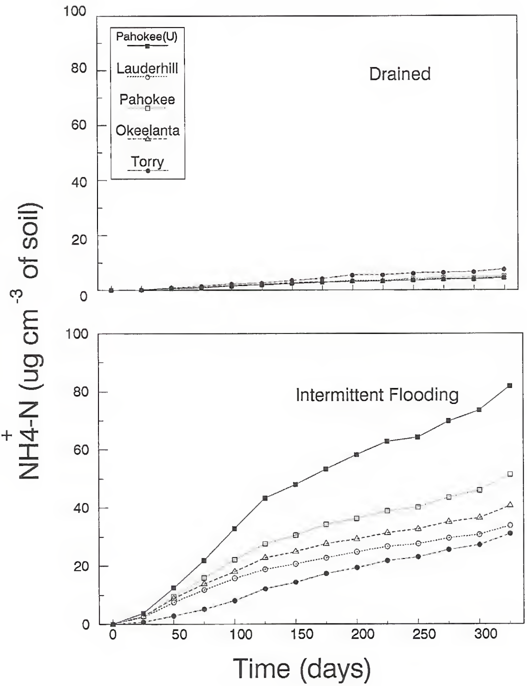

Fig. 6-1. Cumulative NH_4^+-N released from organic soils under drained and intermittent flooded conditions.

released during organic matter decomposition is rapidly nitrified, resulting in little or no NH_4^+-N accumulation in the soil (Tate, 1977; Reddy, 1982). However, under intermittent-flooded conditions the amounts of NH_4^+-N released were more than seven times higher (2.39 to 6.29 μg N cm^{-3} of soil per leaching period) than those measured in drained soils (Fig. 6-1). Accumulation of NH_4^+-N under intermittent-flooded conditions occurs as a result of dissimilatory reduction of NO_3^--N to NH_4^+-N during anaerobic respiration (Buresh and Patrick, 1981), and a drastic reduction in the nitrification rate as a consequence of the lack of oxygen (Terry and Tate, 1980). Similar results have been reported from other studies with organic soils from South and Central Florida (Terry and Tate, 1980; Reddy, 1982).

The total amounts of NH_4^+-N released in the leachates under drained and intermittent-flooded conditions are shown in Table 6-5. Total NH_4^+-N released from drained soils ranged from 7.5 to 12.7 kg N ha^{-1} yr^{-1}, which is less than 6% of the total N released from all soils. Under intermittent-flooded conditions, the total NH_4^+-N released ranged from 52 to 138 kg N ha^{-1} yr^{-1}, which represents more than 30% of the total N released in all soils.

Table 6-5. Nitrogen mineralization rates from the upper 15 cm of five organic soils from the EAA.

Soil series	NH_4^+-N			NO_3^--N		
	Drained	Flooded	$LSD_{.05}$§	Drained	Flooded	$LSD_{.05}$
	--------- N mineralized, kg ha^{-1} yr^{-1}† ---------					
Pahokee (U)	7.5	137.8	24.6	339.5	11.0	52.1
Lauderhill	8.0	56.9	4.0	226.0	5.8	84.9
Pahokee	8.7	86.5	13.0	173.1	5.0	32.9
Okeelanta	7.6	68.5	9.3	212.6	6.2	62.3
Torry	12.7	52.2	17.8	109.5	10.3	11.2
$LSD_{.05}$‡	3.0	16.1		57.5	3.6	

Soil series	SON			Total N		
	Drained	Flooded	$LSD_{.05}$	Drained	Flooded	$LSD_{.05}$
	--------- N mineralized, kg ha^{-1} yr^{-1} ----------					
Pahokee (U)	161.9	200.7	69.3	509	345	93
Lauderhill	134.9	105.7	8.2	369	168	93
Pahokee	157.8	139.7	18.7	340	231	60
Okeelanta	120.3	101.1	17.6	341	176	74
Torry	94.9	52.2	15.7	217	180	14
$LSD_{.05}$	9.0	30.8		60	41	

† Average of four replications.
‡ To compare soils within treatments.
§ To compare each soil among treatments.

Nitrate-nitrogen

Nitrate-N mineralized from drained soils ranged from 5.0 to 15.5 μg N cm^{-3} of soil per leaching period over the 325 d of the incubation study (Fig. 6-2). Release of NO_3^--N from all soils was similar during the first 50 d. After 50 d, NO_3^--N released from the uncultivated Pahokee muck was higher ($P \leq 0.05$) than from the other four soils. There were no differences in the amounts of NO_3^--N released from the cultivated Pahokee, Lauderhill, and Okeelanta soils throughout the study. Nitrate-N released from the Torry soil was similar to the other three cultivated soils during the first 175 d. At this point, the N mineralization from this soil started to level off, resulting in the lowest ($P \leq 0.05$) cumulative NO_3^--N release at the end of the incubation period.

The amounts of NO_3^--N released from intermittent-flooded soils ranged from 0.23 to 0.50 μg N cm^{-3} of soil per leaching period over the entire study (Fig. 6-2). Nitrate-N can accumulate in the soil at substantial levels in well aerated organic soils, reaching an optimum at about field capacity (Avnimelech, 1971; Terry, 1980). However, the average NO_3^--N concentrations present under waterlogged conditions are usually too low ($\leq$ 3 mg kg^{-1} of soil) to be of significance as a nutrient, or as a toxic substance

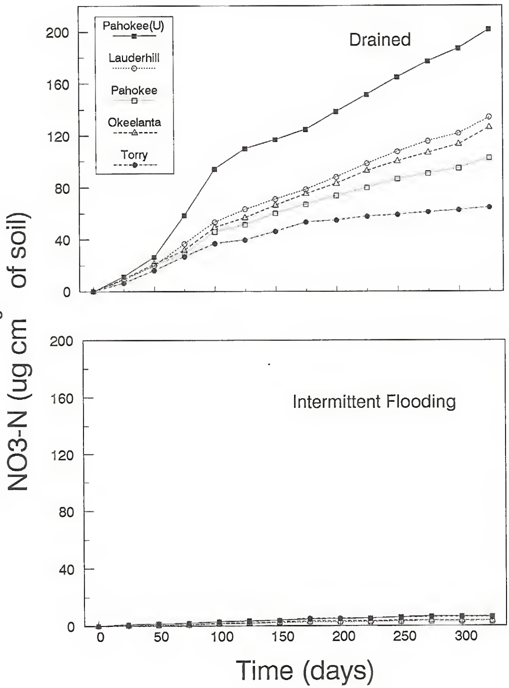

Fig. 6-2. Cumulative NO_3^--N released from organic soils under drained and intermittent flooded conditions.

(Patrick et al., 1985). In flooded soils, reduced conditions changes soil microorganism populations and pathways of organic matter chemical decomposition. After flooding, NO_3^--N is rapidly utilized by facultative anaerobic bacteria, a process called NO_3 respiration or dissimilatory NO_3 reduction, resulting in low levels of NO_3^--N being accumulated.

Cumulative NO_3^--N release curves under drained conditions (Fig. 6-2) were better described by a nonlinear regression model (R^2 = 0.99) with the intersection of two linear regression lines occurring around 100 d of incubation. The higher release of NO_3^--N during the first 100 d of the study was probably due to the presence of a higher amount of more easily decomposable materials in that period.

Total NO_3-N released into the leachates from drained soils ranged from 110 to 340 kg ha^{-1} yr^{-1}, which represents 50 to 67% of the total N released during a 1-year study (Table 6-5). Results from intermittent-flooded soils were the opposite of those from drained soils. Total NO_3^--N from flooded soils ranged from 5.0 to 11.0 kg ha^{-1} yr^{-1}, accounting for less than 3% of the total N released during the study.

Soluble organic nitrogen (SON)

Soluble organic N released from drained soils ranged from 4.33 to 7.39 $\mu g\ cm^{-3}$ of soil per leaching period over the entire study (Fig. 6-3). There were no differences ($P \leq 0.05$) in the total amounts of SON released from the uncultivated and cultivated Pahokee soils. However, SON released from these two soils was higher than the amounts released from the other three soils, with Torry showing the lowest release. The average SON released under intermittent-flooded conditions ranged from 4.62 to 9.17 μg cm^{-3} of soil per leaching period (Fig. 6-3). Intermittent flooding significantly increased the amount of SON released by the uncultivated Pahokee ($P \leq 0.05$) with the Okeelanta soil showing the lowest release at the end of the 325-d study.

Total SON released into the leachates from drained soils ranged from 95 to 162 kg ha^{-1} yr^{-1}, which represented 32 to 46% of the total N released (Table 6-5). The amounts of SON released from intermittent-flooded soils ranged from 101 to 201 kg ha^{-1} yr^{-1}, accounting for more than 57% of the total N released during a 1-year period. Flooding increased the amount of SON ($P \leq 0.05$) released into the leachates only in the uncultivated Pahokee and Torry mucks. The other soils showed either no difference (Cultivated Pahokee) or more SON released under drained conditions (Lauderhill and Okeelanta). Soluble organic N is one of the most important

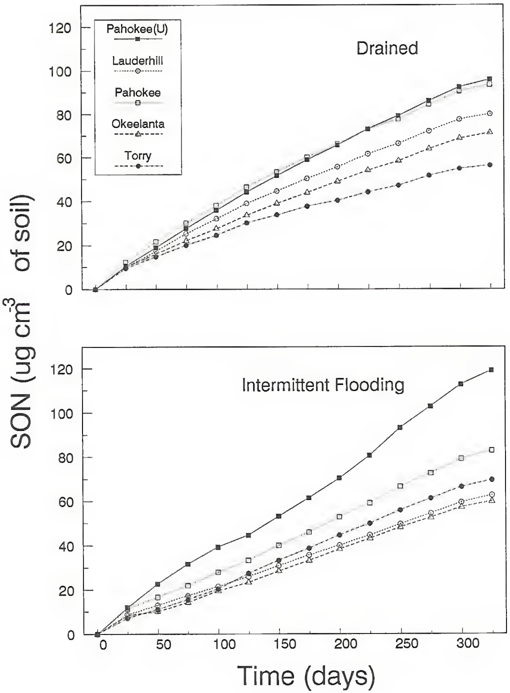

Fig. 6-3. Cumulative SON released from organic soils under drained and intermittent flooded conditions.

components of total N, and is the fraction that is more readily available for microbial oxidation to NH_4^+-N and subsequently to NO_3^--N. However, in leaching studies this fraction is periodically taken out of the system, not allowing the nitrifying bacteria to complete the nitrification cycle. Therefore, leaching studies measuring NO_3^--N can underestimate mineralization potential of soils (Smith et al., 1980).

Total N mineralization of the surface 15 cm of soil based on a 1-year period ranged from 217 to 509 kg ha^{-1} yr^{-1} under drained conditions, and from 180 to 350 kg ha^{-1} yr^{-1} under intermittent-flooded conditions (Table 6-5). The uncultivated Pahokee showed the higher ($P \leq 0.05$) N mineralization rates under intermittent flooded and drained conditions. These results are in contrast to those of Terry (1980), who found higher N mineralization in cultivated soils. The uncultivated site had been drained for more than 10 years; this allowed the surface soil layer to be continually aerated to undergo organic matter oxidation. Although C was not measured in the leachates, the darker color of the leachates from the uncultivated soil indicated that soluble organic C was present in substantial amounts. The higher N mineralization from the uncultivated soil was probably due to a higher percentage of easily decomposable organic materials in this soil than in the cultivated soils. In addition, disturbance of the uncultivated soil at the

time of sampling may have induced a higher N release in this soils. In cultivated soils, undecomposed material is mixed with the more decomposed material from the surface layer during land preparation. Therefore, the chances of having more undecomposed materials in the surface layer of cultivated soils are greater.

Torry muck was the soil that showed the lowest N mineralization rate under drained and intermittent-flooded conditions (Table 6-5). Torry mucks is a soil that contains ≥ 40% by volume of mineral matter (McCollum et al., 1976; Schuster et al., 1986). Volk (1973) showed that for any given temperature and water-table depth, percentage of ash, C, and bulk density were inversely related to evolved C. The lower organic C of these soils (16.5% compared to > 37% for the other soils) in combination with the mineral content are the main reasons for the lower N mineralization rate shown by these soils. Despite these results, Torry muck is one of the most productive organic soils in the EAA, and probably one that is going to be around for a longer period of time because it is more resistant to soil subsidence (Volk, 1973).

Phosphorus

Cultivated organic soils released more P than the uncultivated soil. The amount of SRP released from drained soils ranged from 0.17 to 2.92 μg P cm^{-3} of soil per 25-d

leaching period (Fig. 6-4). Total amounts of SRP from the surface 15 cm of soil during the entire incubation study ranged from 3.6 to 64.0 kg P ha^{-1} yr^{-1} from all soils (Table 6-6). Average amounts of P as SRP released from intermittent-flooded soils ranged from 0.90 to 3.5 μg cm^{-3} of soil per leaching period (Fig. 6-4). These amounts represented an annual release rate of 19.7 to 76.6 kg P ha^{-1} yr^{-1} from all soils studied (Table 6-6). Total SRP released into the leachates represents 65 to 89% and 55 to 90% of the total P released into the effluents from all soils under drained and intermittent-flooded conditions, respectively.

Average amounts of total P released from drained soils ranged from 0.25 to 3.29 μg P cm^{-3} of soil per leaching period (Fig. 6-5). Cumulative amounts of total P released from drained soils (3.31 to 42.76 μg P cm^{-3} of soil) during the entire incubation study, represented only 2.1 to 2.5% of the total soil P (Table 6-3). Average total P released from intermittent-flooded soils ranged from 1.64 to 4.0 μg P cm^{-3} of soil per 25 d (Fig. 6-5). Cumulative amounts of total P released under intermittent-flooded conditions (21.37 to 51.96 μg P cm^{-3} of soil) during the 325-d incubation study, accounted for only 3 to 14% of the total soil P (Table 6-3). Cumulative amounts of total P released throughout the entire incubation study represented an annual release rate of 5.6 to 72.0 kg P ha^{-1} yr^{-1} for drained soils, and 36.0 to 87.5 kg P ha^{-1} yr^{-1} for intermittent-flooded soils (Table 6-6).

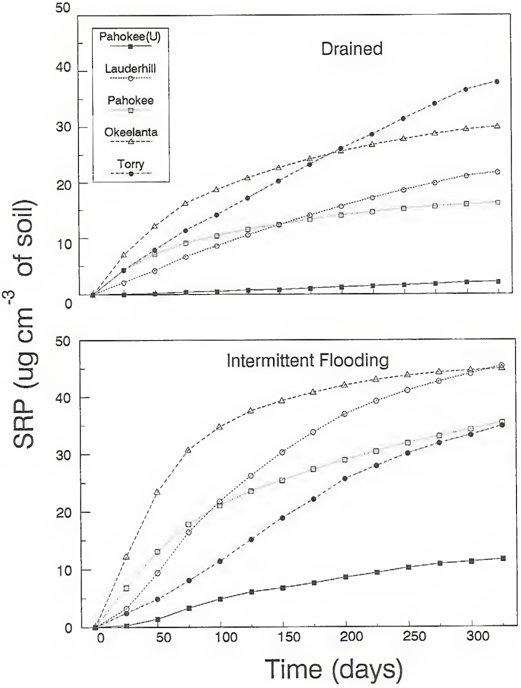

Fig. 6-4. Cumulative SRP released from organic soils under drained and intermittent flooded conditions.

Table 6-6. Phosphorus mineralization rates from the upper 15 cm of five organic soils from the EAA.

	SRP			Total P		
Soil series	Drained	Flooded	$LSD_{.05}$§	Drained	Flooded	$LSD_{.05}$
	--------- P mineralized, kg ha^{-1} yr^{-1}† ---------					
Pahokee (U)	3.6	19.7	11.4	5.6	36.0	33.3
Lauderhill	36.7	76.6	7.9	41.0	84.6	6.7
Pahokee	27.4	59.9	2.2	31.8	67.6	5.7
Okeelanta	50.5	75.8	1.7	56.8	84.3	1.4
Torry	64.0	58.9	22.1	72.0	87.5	26.2
$LSD_{.05}$‡	4.8	10.8		4.9	19.4	

† Average of four replications.
‡ To compare soils within treatments.
§ To compare each soil among treatments.

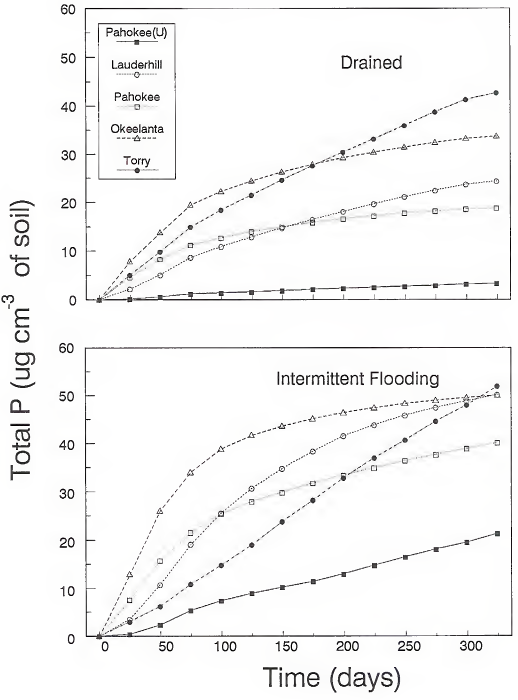

Fig. 6-5. Cumulative total P released from organic soils under drained and intermittent flooded conditions.

Torry muck showed the highest ($P \leq 0.05$) release of SRP and total P (64.0 and 72.0 kg P ha^{-1} yr^{-1}, respectively) under drained conditions (Table 6-6). Total soil P of these soils (1736 μg P cm^{-3} of soil) was more than seven times higher at the beginning (Table 6-3), and more than eight times higher (1682 μg P cm^{-3} of soil) at the end of the study than total soil P from the other four organic soils (Table 6-7). Although, the Torry muck showed the highest P-release rate under drained conditions (42.76 μg P cm^{-3} of soil) during the 325-d incubation period, it only accounts for 2.5% of the total soil P (Table 6-3). These results indicate that small amounts of organic P were mineralized, probably because of the slow organic matter decomposition of these soils. Volk (1973) showed that a Torry muck from the Everglades at a water-table depth of 25 cm lost only 0.64 cm of soil yr^{-1}, at a temperature of 35 °C, while Montverde and Terra Ceia mucks lost 2.08 and 1.01 cm soil yr^{-1}, respectively. Torry mucks are high in sepiolite, which form a clay-organic complex less accessible to the oxidation process (Greenland, 1965). Higher bulk densities of these soils might also lead to lower oxidation rates due to poorer soil aeration. Despite the lower total P releasing rates shown by Lauderhill, Okeelanta, and the cultivated Pahokee, their cumulative amounts of total P released under drained conditions during the study (Fig. 6-5), represented 21.6, 8.7, and 8.5% of the total soil P, respectively (Table 6-3).

Table 6-7. Nitrogen and P content of the organic soils at the end of the incubation study.

	Nitrogen†		Phosphorus†	
Soil series	Water soluble	Total kjeldahl	Mehlich I-extractable	Total
	mg kg^{-1}	g kg^{-1}	- μg P cm^{-3} of soil -	
Pahokee (U)	46.1	33.1	2.0	265
Lauderhill	26.2	30.7	14.2	226
Pahokee	37.4	33.0	4.1	178
Okeelanta	25.2	29.8	4.5	111
Torry	17.7	16.1	132.4	1682
$LSD_{.05}$	3.8	0.6	6.2	26

† Avearge of 8 observations.

These figures indicate that more organic P was mineralized from these organic soils. The uncultivated Pahokee showed the lowest total P mineralization rate (5.57 kg ha^{-1} yr^{-1}) of all soils studied (Table 6-6) under drained conditions. Most of the total P in virgin Histosols is in the organic form and must be mineralized before it can be utilized by plants (Waksman, 1936; Lucas, 1982). Reddy (1983) reported that about 74% of the total P of cultivated and virgin Pahokee mucks was in the organic form. Slow P mineralization is probably the reason for the low rate of P released from the uncultivated Pahokee under drained conditions (Fig. 6-5).

Flooding significantly increased ($P \leq 0.05$) the amount of total P released into the effluents (Table 6-6). Torry muck was the only soil that showed no differences ($P \leq 0.05$) in total P released under either drained or intermittent-flooded conditions. The average amounts of total P released from intermittent-flooded soils (Fig. 6-5) (1.64 to 4.0 μg P cm^{-3} of soil per 25 d) represented an annual release rate of 36.0 to 87.5 kg P ha^{-1} yr^{-1} (Table 6-6). Total P released from intermittent-flooded soils at the end of the study was 1.2 to 6.4 times higher than total P released from drained soils. However, the highest increase for most soils occurred during the first 100 d of the study. The uncultivated Pahokee showed the highest increase in total P release under intermittent-flooded conditions. The

increased release of P in intermittent-flooded soils was probably due to the higher solubilization of organic matter during anaerobic decomposition. Intermittent-flooding also increased the release of inorganic P due to the solubilization of Fe, Al, and Ca phosphates (Mahapatra and Patrick, 1969; Reddy, 1987).

Conclusions

Total NH_4^+-N released from intermittent-flooded soils at the end of the study was higher ($P \leq 0.05$) than NH_4^+-N released from drained soils. However, more than 50% of the NH_4^+-N released occurred during the first 125 d of the study. These results suggest that NH_4^+-N accumulation in the organic soils of the EAA under intermittent-flooded conditions is higher during the first months of flooding. After the initial period, NH_4^+-N release decreased with time. This high accumulation of NH_4^+-N in intermittent-flooded soils is the result of the dissimilatory reduction of NO_3^--N to NH_4^+-N during anaerobic respiration, and the drastic reduction in nitrification due to the lack of oxygen. Well aerated organic soils rapidly nitrified NH_4^+-N released during organic matter decomposition, resulting in little NH_4^+-N accumulation. Total NH_4^+-N released from drained soils represented less than 6% of the total N released from all soils, compared with more than 30% released from intermittent-flooded soils.

Nitrate-N released from drained soils was higher ($P \leq 0.05$) than NO_3^--N released from intermittent-flooded soils, as expected. Total NO_3^--N released from drained soils represented 50 to 67% of the total N released during a 1-year study, compared to less than 3% from intermittent-flooded soils. Nitrate-N released from drained soils was higher during the first 125 d, where more than 50% of the total NO_3^--N was released from all soils studied. Higher NO_3^--N at the beginning of the study was probably due to the breakdown of the more easily decomposable organic material by the microorganisms. In the later stages of the study, NO_3^--N release started to decline, as the more lignified material remained. Soluble organic N from intermittent-flooded soils was higher ($P \leq 0.05$) only in the uncultivated Pahokee and the Torry muck. The other three soils showed either no difference or a higher release under drained conditions.

Flooding significantly increased ($P \leq 0.05$) the amount of total P released into effluents. Total P released from intermittent-flooded soils at the end of the study was 1.2 to 6.4 times higher than total P released from drained soils, with the higher release occurring during the first 100 d of the study. Soluble reactive P released from four of the intermittent-flooded soils was two to five times higher than SRP released from drained soils. Torry muck was the only soil that showed no differences ($P \leq 0.05$) in SRP

and total P released under intermittent flooded and drained conditions. Total SRP released during a 1-year period represented 65 to 89% and 55 to 90% of the total P released into the effluents from all soils under drained and intermittent-flooded conditions, respectively. The effect of intermittent flooding on total P release was greater in the uncultivated soil than in the cultivated soil. Total P released from the flooded uncultivated Pahokee was 6.4 times higher than total P released under drained conditions. In contrast, total P released from cultivated flooded soils was only 1.2 to 2.2 times higher than that released from drained soils. Although, the effect of intermittent flooding on total P release was less in cultivated soils, total P release from these soils was more than twice the total P released from the uncultivated soil. Total P released from the uncultivated Pahokee was only 5.0 and 36.0 kg ha^{-1} yr^{-1} under drained and intermittent-flooded conditions, respectively. Total P released from the surface 15 cm of cultivated soils under drained (31.7 to 72.0 kg ha^{-1} yr^{-1}), and intermittent-flooded conditions (67.6 to 87.5 kg ha^{-1} yr^{-1}) would approximately meet crop requirements.

The process of N mineralization from organic soils releases more N than crops need. Total N released from the surface 15 cm of drained soils (217 to 509 kg ha^{-1} yr^{-1}) is sufficient for most crops grown in organic soils, considering that a similar or larger quantity of N is

mineralized from the next 25 cm of soil (Terry, 1980). It has been estimated that vegetable crops (two crops per year) grown in Florida remove about 200 to 420 kg N ha^{-1} (Lorenz and Maynard, 1980) and 50 to 70 kg P ha^{-1}, while a crop of sugarcane removes from 80 to 100 kg N ha^{-1} and 22 to 27 kg P ha^{-1} (Barnes, 1974; Andreis, 1975). According to these results, total P released from the surface 15 cm of these organic soils will not quite satisfy the requirements of a commercial crop. Crops grown in the organic soils from the EAA have been shown to respond to P fertilization (Gascho and Kidder, 1979) indicating the low P-releasing capacity of these soils.

CHAPTER 7
SUMMARY AND CONCLUSIONS

Introduction

Soil variability is the product of soil-forming factors operating and interacting over a continuum of spatial and temporal scales. However, soil variability in the Everglades Agricultural Area (EAA) has been further increased by drainage, intensive cropping, and the extensive construction of roads and canals.

Drainage of organic soils for agricultural purposes results in the loss of soil through rapid breakdown of organic matter. In an attempt to reduce soil loss through biological oxidation, growers from the EAA flood fallow fields during the summer. The wetting and drying cycle of flooding has a marked effect on the physical, chemical, and biological properties of organic soils, thus affecting the availability of the different forms of N (NH_4^+, NO_3^-, and SON) and P (ortho-P (PO_4^{-3}) and soluble organic phosphorus).

The purpose of this chapter is to summarize the work presented in the preceding chapters. The broad objective of this research was to obtain information of field and regional soil spatial variability of the Histosols of the EAA. Effects of intermittent flooding and drained

conditions on N and P release were also measured. To achieve these objectives, geostatistical analysis of local and regional data and a laboratory incubation study were conducted.

Semi-variograms

Results showed that several selected soil chemical properties from selected Histosols of the EAA are spatially dependent. Semi-variograms were useful in detecting within-field soil variability in selected organic soils of the EAA. The structure of spatial dependence displayed by the semi-variograms gave important information about the direction and range of dependency of selected chemical properties.

Soil pH, Mg_{MI}, Mn_{MI}, and Fe_{MI} were the only chemical properties that showed anisotropic variability. Soil Mn_{MI} from the Pahokee muck was the element that displayed the highest spatial variability. Anisotropic semi-variograms showed that road spoils have greater influence on soil variability than ditch spoils.

The range of spatial dependence of most of the soil properties was > 100 m in all locations. These results suggested that soil samples collected at 100 m or less are spatially dependent. Whenever a strong relationship exists, the sampling distance should be equal to the range of the semi-variogram model. In general, Torry muck was the most

uniform soil series, while Okeelanta muck showed the highest variability.

Results from this study give us important information on the behavior and spatial variability of within field chemical properties in the EAA. Spatial variability information can be used to optimize sampling designs for soil-testing purposes.

Block Kriging

Kriged-contour maps are a valuable technique to evaluate soil spatial variability in the EAA. Contour maps clearly show the influence of road and ditch spoils on field soil variability. Depth of organic layer to the limestone bedrock is also an important factor influencing field variability in the EAA. Visual analysis of contour maps show that an area approximately 40 to 50 m from the roads and 25 to 30 m from each side of the ditches should be avoided during soil sampling.

Block kriging was also helpful in mapping soil variability due to cropping history. Phosphorus concentrations in the sweetcorn-fallow field of Okeelanta muck were twice as high as those shown by the sugarcane-fallow field. Similar P variability pattern was displayed by the sod field (high P values) and sugarcane-fallow field (low P values) from the Lauderhill muck. Block-kriged maps verified results from the previous chapter that the

Okeelanta muck was the most variable site, while Torry muck was the most uniform site.

Soil variability between fields in the same location and among soil series is large. Soil pH was the most uniform soil property requiring only four to six soil samples to produce a value with 5% error at the 95% confidence level. In contrast, Mg and P required 15 to 20 samples to produce values within 20% of the population mean with 95% confidence level. A practical number for K is also 15 to 20 samples to produce K values within 20% of the population mean at the 90% confidence level. The acceptance of large relative errors to minimize sampling efforts indicate that good soil sampling is a difficult task in the EAA.

Regional Variability

Regional kriged maps showed variability patterns due to soil type and soil management. Regional maps show that the average soil pH_w in the EAA ranges between 6.4 to 6.6. High pH values in the EAA may be related to the proximity of the limestone bedrock due to soil subsidence.

The highest concentrations of P_w and K_a were located in some of the most intensive cultivated areas. Thus, soil P_w and P_a variability in the EAA is strongly influenced by cropping and soil management. Soil P_a is also influenced by soil management, however, soil series appears to have a

greater influence on its variability. The highest P_a concentrations were located where most of the Torry muck soils of the EAA are located. Total P from Torry mucks is approximately three to six times higher than total P in the other soil series of the EAA. Soil P_w/P_a contour maps showed important information of areas with high P loss potential.

An additional advantage of kriging is that an error term is also calculated, providing a measure of interpolation reliability. The estimation variance maps indicate areas where additional sampling is needed to increase the confidence levels of the map.

Nitrogen and Phosphorus Release

Total NH_4^+-N released from intermittent flooded soils was more than seven times higher than the amounts released from drained soils. Under well drained conditions, NH_4^+-N released during organic matter decomposition is rapidly nitrified, resulting in very little NH_4^+-N accumulation in the soil. However, under flooded conditions NH_4^+-N accumulates in the soil. In intermittently flooded organic soils, dissimilatory reduction of NO_3^--N to NH_4^+-N is probably one of the most significant process during anaerobic respiration. Total NH_4^+-N released from drained soils represents less than 6% of the total N released from

all soils, compared to more than 30% released from intermittent flooded soils.

Soil NO_3^--N released from drained soils was higher ($P \leq 0.05$) than NO_3^--N released from intermittent flooded soils. Total NO_3^--N released from drained soils represented 50 to 67% of the total N released during one year, compared to less than 3% from intermittent flooded soils. Nitrate-N accumulates substantially in well-aerated soils, being optimum at about field capacity. In contrast, the average NO_3^--N in flooded soils is usually $\leq$ 3 mg kg^{-1} soil.

There were no differences in the amounts of SON released from drained and intermittent-flooded soils. However, flooding significantly increased the amount of SON released from the uncultivated Pahokee and Torry mucks. Total SON released from drained soils accounted for 32 to 46%, while that of intermittently flooded soils accounted for more than 57% of the total N released during the entire study.

Total N released from drained soils ranged from 217 to 509 kg ha^{-1} yr^{-1}. In contrast, total N released from intermittent flooded soils ranged from 168 to 345 kg N ha^{-1} yr^{-1}. The uncultivated Pahokee showed the highest N mineralization rates under both, drained and intermittently flooded conditions. This probably resulted from disturbing the soil during sampling causing a rapid breakdown of the easily decomposable organic material. Torry muck showed the

lowest N mineralization rate of all soils, likely due to low C content (16.5%) and to greater resistance of this soil to organic matter breakdown.

Intermittent flooding significantly increased the amounts of SRP and total P released from Histosols. Total P released from intermittent-flooded soils (36 to 87 kg P ha^{-1} yr^{-1}) was approximately two to six times higher than total P released from drained soils (6 to 72 kg P ha^{-1} yr^{-1}).

Soluble reactive phosphorus (SRP) released from four intermittent-flooded soils was two to five times higher than that released from drained soils. Torry muck was the only soil that showed no significant differences in SRP and total P released under either treatment. Total SRP released accounted for 65 to 89% and 55 to 90% of the total P released in one year under drained and intermittently flooded conditions, respectively.

Torry mucks showed the highest release of SRP and total P under drained and intermittent-flooded conditions, while uncultivated Pahokee showed the lowest. However, the uncultivated Pahokee showed the largest SRP and total P release due to intermittent flooding. In contrast, total P released from Torry muck at the end of the study accounted for only 2.5% of that in this soil. These results indicate that small amounts of P were mineralized, probably because of the slow organic matter decomposition of these soils. Total soil P from Torry mucks (1682 μg P cm^{-3} of soil) was

more than seven times higher than total P from the other soils.

The increased release of P under intermittent-flooded conditions is probably due to the higher solubilization of organic matter during anaerobic decomposition. Flooding also increased the release of inorganic P due to the solubilization of Fe, Al, and Ca phosphates.

APPENDIX A
SUMMARY STATISTICS OF EXPERIMENTAL SOILS

Table A-1. Summary statistics of soil chemical properties from the surface 15 cm of a Lauderhill muck.

Variable†	Mean	Range	Variance	CV (%)
	- Analytical Research Laboratory, Gainesville‡ -			
pH-H_2O	6.3	5.7 - 7.5	0.067	4.1
pH-$CaCl_2$	6.0	5.5 - 7.2	0.071	4.4
Ca, g kg^{-1}	9.4	1.8 - 12	1.36	12
Mg, g kg^{-1}	1.5	0.30 - 1.9	0.028	11
K, g kg^{-1}	0.36	0.04 - 0.92	0.022	41
P, mg kg^{-1}	46	6.2 - 110	257	35
Zn¶, mg kg^{-1}	1.2	0.29 - 2.5	0.265	42
Cu, mg kg^{-1}	0.33	0.04 - 0.63	0.024	48
Mn, mg kg^{-1}	0.95	0.10 - 9.1	0.411	68
Fe, mg kg^{-1}	4.2	0.80 - 7.6	0.685	20
	-------- Soil Testing Laboratory, EREC§ --------			
P_w, mg kg^{-1}	12	3.8 - 31	30.7	47
P_a, mg kg^{-1}	77	41 - 169	707	34
K, g kg^{-1}	0.29	0.13 - 0.70	0.012	38

† Measurements were calculated from 184 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable P), P_a and K (0.5 M acetic acid extractable).
¶ Mehlich Zn and Cu were calculated from 84 observations.

Table A-2. Summary statistics of soil chemical properties from the surface 15 cm of a Pahokee muck.

Variable†	Mean	Range	Variance	CV (%)
	- Analytical Research Laboratory, Gainesville‡ -			
pH-H_2O	5.3	4.9 - 7.1	0.061	4.6
pH-$CaCl_2$	5.1	4.7 - 6.8	0.052	4.5
Ca, g kg^{-1}	10	2.0 - 14	1.37	11
Mg, g kg^{-1}	1.3	0.27 - 1.8	0.029	13
K, g kg^{-1}	0.22	0.11 - 1.1	0.048	51
P, mg kg^{-1}	49	9.0 - 190	415	42
Zn, mg kg^{-1}	1.8	0.52 - 5.5	0.333	32
Cu, mg kg^{-1}	0.41	0.33 - 0.59	0.0021	11
Mn, mg kg^{-1}	7.3	2.0 - 14	4.40	29
Fe, mg kg^{-1}	2.9	0.94 - 5.0	0.119	12
	-------- Soil Testing Laboratory, EREC§ --------			
P_w, mg kg^{-1}	41	13 - 78	109	26
P_a, mg kg^{-1}	65	39 - 376	1108	51
K, g kg^{-1}	0.35	0.08 - 0.93	0.033	51
Ca, g kg^{-1}	6.4	5.1 - 7.7	0.251	7.9
Mg, g kg^{-1}	1.1	0.70 - 1.6	0.022	14

† Measurements were calculated from 186 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).

Table A-3. Summary statistics of soil chemical properties from the surface 15 cm of an Okeelanta muck.

Variable[†]	Mean	Range	Variance	CV (%)
	- Analytical Research Laboratory, Gainesville[‡] -			
pH-H_2O	4.8	4.3 - 5.5	0.044	4.4
pH-$CaCl_2$	4.4	3.9 - 5.1	0.040	4.6
Ca, g kg^{-1}	8.6	2.3 - 15	4.19	24
Mg, g kg^{-1}	0.58	0.11 - 2.5	0.164	70
K, g kg^{-1}	0.37	0.04 - 1.0	0.038	52
P, mg kg^{-1}	32	0.78 - 101	497	70
Zn, mg kg^{-1}	11	0.24 - 22	17.9	40
Cu, mg kg^{-1}	0.55	0.19 - 1.4	0.035	34
Mn, mg kg^{-1}	10	0.16 - 26	29.7	54
Fe, mg kg^{-1}	20	1.6 - 50	101	51
	-------- Soil Testing Laboratory, EREC[§] --------			
P_w, mg kg^{-1}	37	3.1 - 93	467	58
P_a, mg kg^{-1}	49	7.9 - 167	760	56
K, g kg^{-1}	0.29	0.04 - 0.84	0.022	51
Ca, g kg^{-1}	4.0	1.3 - 6.7	0.782	22
Mg, g kg^{-1}	0.35	0.09 - 0.69	0.008	26

† Measurements were calculated from 181 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).

Table A-4. Summary statistics of soil chemical properties from the surface 15 cm of a Torry muck.

Variable†	Mean	Range	Variance	CV (%)
	- Analytical Research Laboratory, Gainesville‡ -			
pH-H_2O	5.4	5.0 - 6.8	0.086	5.4
pH-$CaCl_2$	5.0	4.6 - 6.4	0.089	6.0
Ca, g kg^{-1}	6.8	5.6 - 8.3	0.327	8.4
Mg, g kg^{-1}	0.72	0.52 - 1.2	0.121	17
K, g kg^{-1}	0.46	0.19 - 0.81	0.019	30
P, mg kg^{-1}	94	61 - 152	246	17
Zn, mg kg^{-1}	10	1.8 - 17	7.25	27
Cu, mg kg^{-1}	0.28	0.13 - 0.48	0.005	24
Mn, mg kg^{-1}	28	3.9 - 62	153	44
Fe, mg kg^{-1}	7.4	2.6 - 12	2.51	21
	-------- Soil Testing Laboratory, EREC§ --------			
P_w, mg kg^{-1}	25	3.0 - 37	32.3	23
P_a, mg kg^{-1}	78	50 - 148	239	20
K, g kg^{-1}	0.29	0.10 - 0.57	0.010	34
Ca, g kg^{-1}	3.0	1.9 - 6.6	0.569	25
Mg, mg kg^{-1}	0.48	0.32 - 1.3	0.017	27

† Measurements were calculated from 185 observations.
‡ Mehlich I-extractable nutrients.
§ P_w (water-extractable P), P_a, K, Ca, and Mg (0.5 M acetic acid extractable).

Table A-5. Means of ash and total content of selected elements from the surface 15 cm of four organic soils from the EAA.

Soil† property	Soil series			
	Lauderhill	Pahokee	Okeelanta	Torry
Ash (%)	17	15	28	57
Ca, g kg^{-1}	51	43	19	16
Mg, mg kg^{-1}	3949	2993	768	12890
K, mg kg^{-1}	517	737	500	1616
P, mg kg^{-1}	646	589	362	2310
Zn, mg kg^{-1}	20	21	35	102
Cu, mg kg^{-1}	27	27	26	8
Mn, mg kg^{-1}	46	65	28	524
Fe, mg kg^{-1}	4965	2201	3261	1306

† Means were calculated from 90 observations.

APPENDIX B
ISOTROPIC AND ANISOTROPIC SEMI-VARIOGRAMS

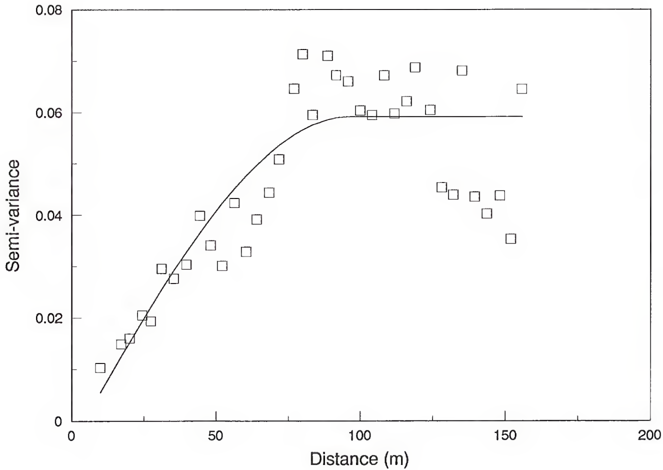

Fig. B-1. Isotropic semi-variogram of soil pH_w from a Lauderhill muck.

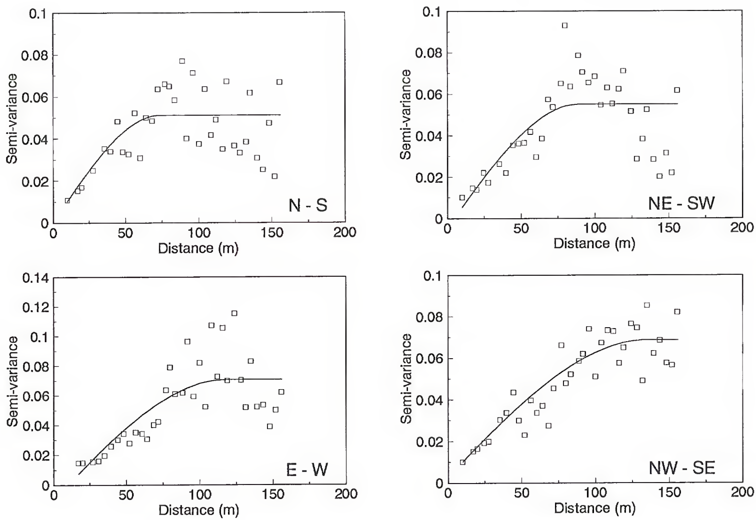

Fig. B-2. Direction-dependent semi-variograms of soil pH_w from a Lauderhill muck.

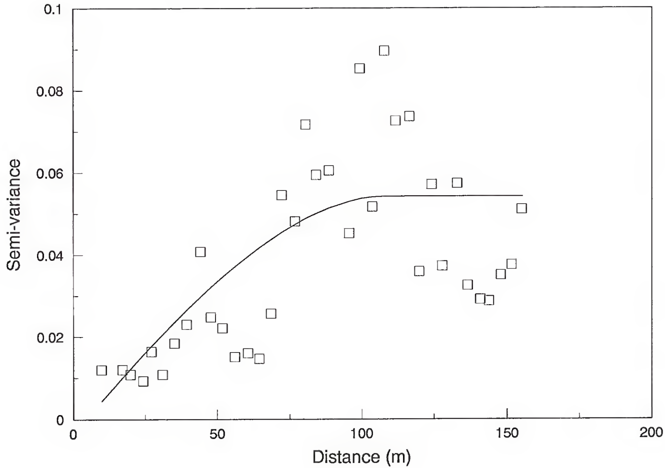

Fig. B-3. Isotropic semi-variogram of soil pH_w from a Pahokee muck.

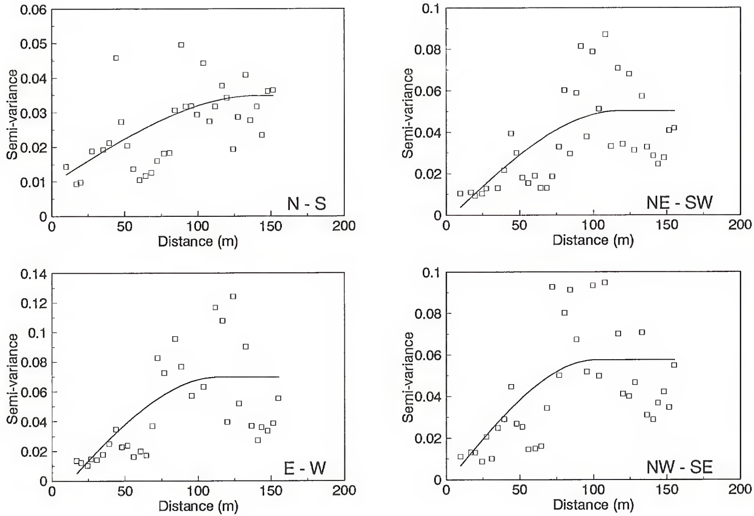

Fig. B-4. Direction-dependent semi-variograms of soil pH_w from a Pahokee muck.

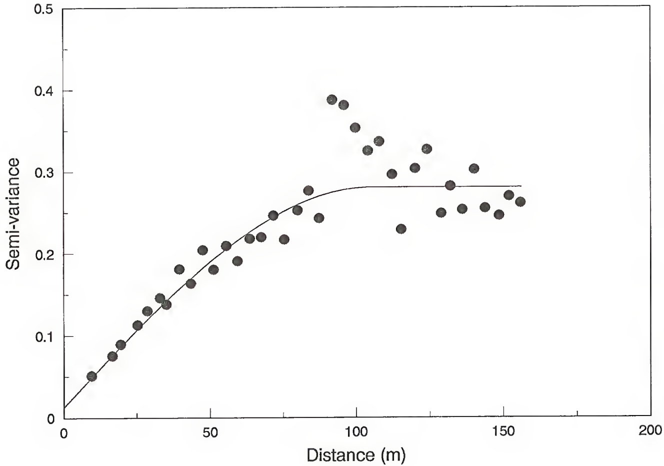

Fig. B-5. Isotropic semi-variogram of soil Fe_{MI} from an Okeelanta muck.

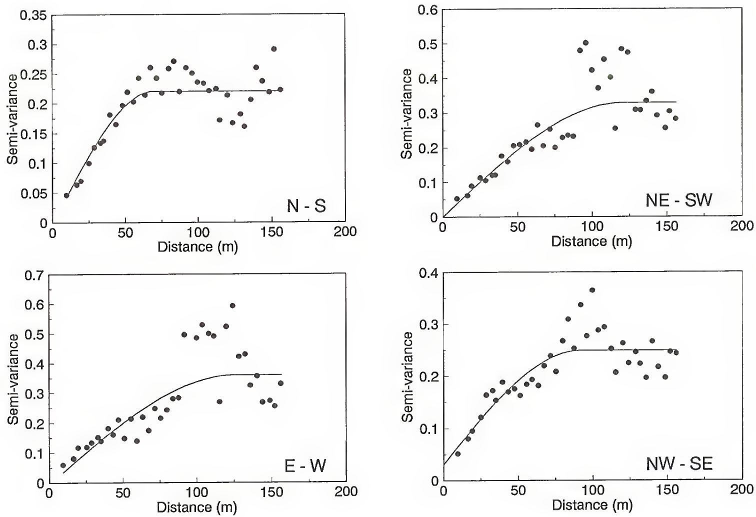

Fig. B-6. Direction-dependent semi-variograms of soil Fe_{MI} from an Okeelanta muck.

APPENDIX C
REGIONAL CONTOUR MAPS

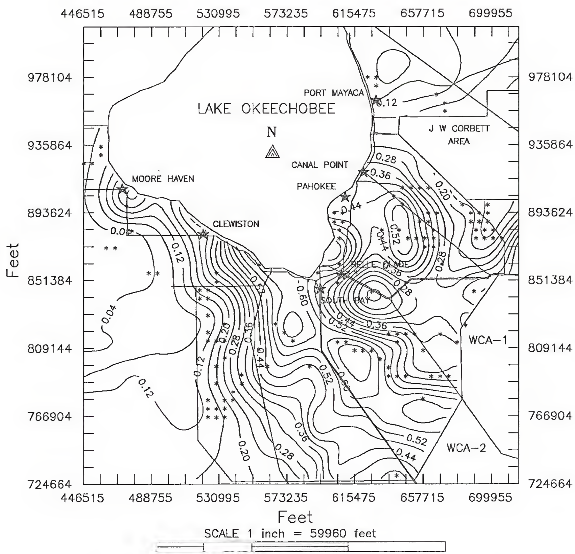

Fig. C-1. Block-kriged contour map of soil Mg_a (g L^{-1}) from the EAA and surrounding areas. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

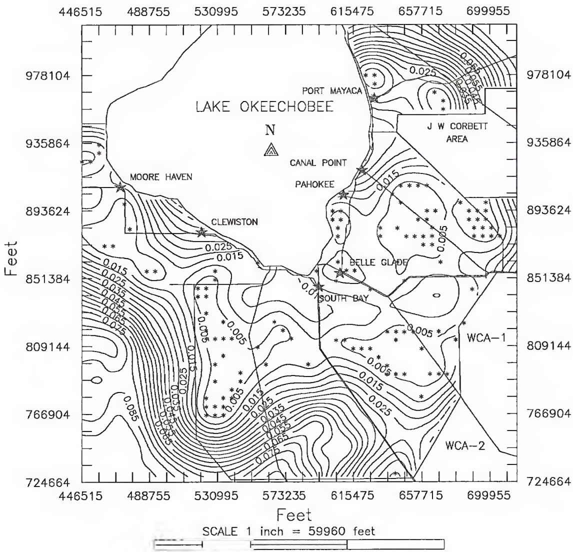

Fig. C-2. Block-kriged contour map of soil Mg_a estimation variance from the EAA and surrounding areas. Contour lines are in units of $(g\ L^{-1})^2$. Official State Plane Coordinate units are ft, therefore, units were not converted to SI units.

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BIOGRAPHICAL SKETCH

Orlando Antonio Diaz was born on 17 Sept. 1957, in the western city of Metapan, El Salvador. Orlando graduated from the Instituto Nacional de Metapan with a high school diploma in 1976. He enrolled in the National School of Agriculture "Roberto Quiñonez" in El Salvador in 1977 and received the diploma of "Agronomo" in 1980.

In April 1980, Orlando was awarded a scholarship from the government of El Salvador to continue studies in the United States. He was enrolled at the University of Florida in the spring of 1981, where he received a bachelor's degree in Soil Science in April 1983. In August 1983, Orlando was accepted for a graduate program in the Soil Science Department, receiving a Master of Science degree in April of 1986.

In August 1986, Orlando was awarded a Soil Science Research Assistantship from the University of Florida to work on his dissertation project concerning soil spatial variability in the Everglades Agricultural Area.

Orlando has been a member since 1984 of the American Society of Agronomy and Soil Science Society of America. He is also a member of the honor societies Gamma Sigma Delta and Sigma Xi.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Edward A Hanlon

Edward A. Hanlon, Chair
Associate Professor of
Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

David L. Anderson, Cochair
Associate Professor of
Agronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Mary E. Collins

Mary E. Collins
Associate Professor of
Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Kenneth M Portier

Kenneth M. Portier
Associate Professor of
Statistics

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Tzu L. Yuan

Tzu L. Yuan
Professor Emeritus of
Soil Science

This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1990

Jack L. Fry

Dean, College of Agriculture

Dean, Graduate School